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Indoor Air Quality in Photocopy Centers, Nanoparticle Exposures at Photocopy Workstations, and the Need for Exposure Controls

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Abstract

Background: Photocopiers emit large amounts of nanoparticles (NP) and are a significant source of indoor air pollution. These emissions induce airway inflammation, irritation, and systemic oxidative stress in humans, lung injury and inflammation in animals, and cytotoxicity and epigenetic modifications *in vitro*. However, little is known regarding NP exposures at the workstation in the photocopy work environment, or the extent and use of emission controls.

Objective: To survey the photocopy work environment with regards to emissions controls and to evaluate IAQ with emphasis on NP exposure at the operator's workstation.

Methods: Work process, physical characteristics of the centers, and use of controls were recorded. Particle total number concentration (TNC), temperature, carbon dioxide, carbon monoxide, and percent relative humidity were measured during a random workday.

Results: Geometric mean (GM) TNC at workstations ranged between 1900 and 23 000 particles cm^{-3}, GSD 1.2–2.8, and maximum of 217 000 particles cm^{-3}. Fresh air ventilation was found to be less than American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) guidelines in 7 of 15 centers. Only one center used any type of emissions control. Elevated TNC at workstations was significantly correlated with number of copies ($r = 0.72$). While indoor/outdoor TNC ratios might be expected to be ≤1.0, the ratio here was >1.0 in 40% of centers visited, supporting the finding that copier emissions are a significant source of indoor air pollution. Number of copies per day was the most significant contributor to TNC.

Conclusion: High NP concentrations at workstations were common and specific emission controls almost nonexistent. While 46% of copy centers had insufficient ventilation, high exposures were documented even for cases when ASHRAE ventilation guidelines per person were met or exceeded. We present various options to address IAQ in photocopy environment, including new clean photocopy technologies, engineering controls, and a comprehensive awareness campaign to improve the environmental health and safety, design, and operational conditions of these workplaces.

Keywords: engineered nano-materials; Nano EH&S; nanoparticles; photocopying; toner

Introduction

Elevated levels of suspended particulate matter (PM) contribute to poor indoor air quality (IAQ). Ultrafine particles (UFP), also known as nanoparticles, is a fraction of PM with mobility diameter of <0.1 µm (referred to hereafter as NP). Hard copy devices (HCDs) including laser printers (LPs) and photocopiers (PCs) have become ubiquitous in indoor environments, and can be found practically in every single office or hallway, from kindergartens to elderly homes, from travel agencies to hospitals, and retail establishments. PCs and LPs share many similarities, including dry toner formulations that are very similar in composition [including the addition of engineered nanomaterial (ENM) additives], and both rely on a charge transfer combined with high heat to create and affix an image to paper (Bello *et al.*, 2013; Pirela *et al.*, 2014b; Martin *et al.*, 2015).In addition, there are at least 21 000 businesses in the United States involved in commercial document duplication and printing, employing ~160 000 full-time employees (FTE) (Pirela *et al.*, 2014a; Martin *et al.*, 2015). IAQ deterioration in commercial printing and photocopying centers due to continuous operation of these devices could be significant. Yet, industry wide surveys on the design characteristics of the work environment of photocopy centers, engineering controls, NP at operators' workstations, and IAQ are limited to studies described below.

HCDs have been shown to emit significant amounts of NP during and after printing, with median diameters often between 20 and 38 nm (He *et al.*, 2007; Adetunji *et al.*, 2009; Bello *et al.*, 2013; Pirela *et al.*, 2014a). Most studies of HCD emissions focus on LPs. In contrast to LPs, exposure and emissions studies in working PC centers are scarce. Lee and Hsu (2007) found PC centers in Taiwan to be cramped with equipment, poorly ventilated, with extremely high PM loads. In a recent study, we collected extensive real-time PM area measurements concurrent with integrated air samples for analysis of metals, organic and inorganic carbon, as well as for exploratory analysis of anions and cations. We found weekly mean NP number concentrations to be up to 12 times greater than background mean NP concentrations measured in the same copy center(s), whereas daily mean NP concentrations were up to 22 times the ambient indoor average, and maximum bursts were measured over 700 times the background (Martin *et al.*, 2015).

Historically, HCDs have been known to emit VOCs and ozone into the indoor air (Lee *et al.*, 2001; Kagi *et al.*, 2007). However, more recent reports have shown very low concentrations of these gaseous pollutants, often indistinguishable from background in PC centers (Lee *et al.*, 2001; Bello *et al.*, 2013; Kowalska *et al.*, 2014). Such reductions in gaseous pollutants may be, at least partially, a result of improvements in both HCD design and toner formulations. We recently examined 33 PC and LP toner formulations and found ENMs in all samples. It has also been shown that these ENMs may become detached from the unused, larger toner particles (Byeon and Kim, 2012; Martin *et al.*, 2015), and may pass through the printing operation and into the indoor air along with incidental NP released during normal HCD use (Bello *et al.*, 2013; Pirela *et al.*, 2014b; Martin *et al.*, 2015). These findings raise concerns for employees, customers, and sensitive subpopulations (i.e. asthmatics, COPD patients, and immunocompromised individuals). This concern is further substantiated by recent studies showing emitted NP in copy centers (which are a mixture of incidental NP and engineered NP present in the toners and paper) induces upper airway inflammation and oxidative stress in healthy volunteers after a short (<6-h) exposure at an average of 20 000–30 000 particles cm^{-3}, (Khatri *et al.*, 2012), and in the chronically exposed workforce (Elango *et al.*, 2013). Moreover, incidental NP emissions from hardcopy devices have been shown to be cytotoxic and genotoxic in laboratory models as well as field studies involving healthy human subjects working at PC centers (Goud *et al.*, 2004; Gadhia *et al.*, 2005; Tang *et al.*, 2012; Pirela et al., 2013, 2015; Khatri *et al.*, 2013a; Sisler *et al.*, 2014; Lu *et al.*, 2015). NPs have been shown to be more toxicologically potent than their larger counterparts, emitted from the same PCs (Khatri et al., 2013a,b). Moreover, NPs from HCDs were found in a recent study to be toxicologically more potent than other comparative nanomaterials, including the well-studied welding fumes, diesel exhaust, and CuO NPs (Pirela *et al.*, 2013).

There are also limited case studies linking emissions from HCDs and HCDs operators' health. D'Alessandro *et al.* (2013) reports on a case of severe chronic coughing from emissions from HCDs, which resolved after removal of the patient from the HCD environment. Upon re-challenge with HCD emissions to the subject, symptoms immediately reappeared, providing good evidence HCD emissions were the causal factor. Theegarten et al. presented a case of an office worker with severe gastrointestinal distress and weight loss. Clusters of agglomerates of NPs were found in biopsy specimens from the subject's submesothelium. The author attributed observed symptoms to PM emissions from the LP (Theegarten *et al.*, 2010).

Most studies to date are limited in scope and focus on characterization of NP emissions and not on design characteristics and exposure controls in these workplaces. Hence, little is known about the work practices, controls, and overall design characteristics of photocopy centers. Furthermore, it is also unknown if copy center managers and owners are aware of NP emissions during photocopying, or the availability of controls to mitigate such exposures. This work builds on our earlier findings of high NP exposures in eight photocopy centers (Martin *et al.*, 2015). Here, the focus shifts toward assessing the IAQ at occupant workstations in a sample of fifteen high-volume commercial photocopy centers. More specifically, the objective of this work was 2-fold: (i) To assess the overall physical environment and design characteristics of multiple high-speed photocopy and duplicating centers in the Greater Boston Area, especially with regards to the use of exposure control technologies; (ii) To assess NP TNC at the occupant workstation and whether existing IAQ for these environments meet published ASHRAE guidelines.

Methods

Participant recruitment

Participating centers were recruited through internet and business directory searches for digital printing presses and duplicating centers in the northeastern United States. The search covered well known commercial copy chains, in-house office resources, and duplicating centers servicing the academic community. Participants were considered eligible if they housed and operated at least one high-speed PC; have at least one full time employee dedicated to high-speed photocopy operations and routine maintenance and produced a minimum of 1000 copies per day. Participating copy centers were visited on a random working day for field measurements and observations of the following.

Field measurements and observations

For each copy center, detailed information was collected on the following themes using survey forms and/or real-time instrumentation: (i) *The physical layout of the facility* (size, location, number of entrances/exits, number operable or inoperable windows, square meter of floor space, height of the ceiling); (ii) *Photocopying activity* (type color/black-and-white, number, manufacturer, model, and year of the photocopiers), photocopying volume, number of print tasks; (iii) Number of *full-time employees* and their *daily activities* (how and where did they spend their time); (iv) *Exposure controls* (natural or mechanical ventilation), dedicated emission controls, type and design characteristics, and their operating conditions; (v) *Indoor air parameters* [T, %RH, carbon dioxide (CO_2), carbon monoxide (CO)]; and (vi) A*irborne total particle number concentration at workers' workstation during the course of the survey day*.

Ventilation performance, outside fresh air flow per person, was estimated by calculating the difference between average indoor and outdoor average CO_2 measurements (equation 1) (ASTM, 2002). The center required amount of fresh outdoor airflow, per occupant, was calculated in accord with ASHRAE 62.2–2013 (equation 2).

$$Q = 10^6 \left(\frac{G}{C_{\text{in,eq}} - C_{\text{out, eq}}} \right) \quad (1)$$

G represents CO_2 generation rate (l s^{-1}), per person, Q represents fresh outdoor airflow into the indoor zone (l s^{-1}), $C_{\text{in, eq}}$ represents equilibrium CO_2 concentration indoors, and $C_{\text{out, eq}}$ represents equilibrium CO_2 concentration outdoors.

$$Q_r = R_p \times P_z + R_a \times A_z \quad (2)$$

Q_r represents required airflow per person, R_p represents outdoor airflow rate required per person as determined in ASHRAE 62.2–2013, P_Z represents zone population, the number of people in the ventilation zone during typical usage, R_a represents outdoor airflow rate required per unit area as determined in ASHRAE 62.2–2013, A_Z represents zone floor area, the net occupiable floor area for the ventilation zone, (ft^2).

Two real-time instruments were used to measure indoor environmental conditions and particle loads at an occupied workstation (determined at the time of sampling) over the course of a full randomly selected weekday. Instruments were positioned at the workstation as close to the occupants breathing zone as possible (<50 cm away) without interfering with their daily tasks. A Q-Trak IAQ monitor (TSI Q-Trak 7585, TSI, Inc., Shoreview, MN, USA) was used to measure indoor CO_2, CO, temperature, dewpoint temperature, and %RH. A condensation particle counter (TSI CPC 3007, TSI, Inc.) was used to measure total particle number concentration.

At the beginning of each day, the CPC internal time clock was synchronized to the attached laptop PC as a time reference. Prior to beginning measurements, a walk-through survey was conducted in each copy center to determine the presence of confounding particle sources. Due to limited access, indoor background measurements were collected (overnight) in 6 of 15 centers. The CPC was factory calibrated and, prior to data collection each day, passed the field 'zero' test with an inline HEPA filter. The instrument inlet was positioned at a selected operator workstation. Indoor measurements were collected continuously throughout the day, and a minimum of 60 min of outdoor measurements were collected at each sample site. The CPC was setup via on board software to measure NP concentrations at a frequency of 1 Hz. Q-Trak software was configured with an averaging time of 5 min, resulting in 12 data points per hour.

Personal exposure measurements were improvised at the workstation using the CPC and Q-Trak at a constant location. We did not use personal samplers to estimate actual exposure, therefore worker's activities were observed for the duration of measurements to estimate the portion of the day spent at the workstation. Because previous results reported by the authors indicated very low to negligible VOCs and ozone concentrations, we omit these parameters in the present study to focus on NP and common IAQ parameters (Khatri *et al*., 2012; Bello *et al*., 2013).

Data analysis

Physical characteristics of each copy center were summarized through observation and physical size measurements. Raw data from real-time instruments were downloaded to Microsoft Excel 2010 and subsequently into SAS v. 9.4 (SAS Institute, Cary, NC, USA) and PASW v. 17.0 (IBM, San Diego, CA, USA) for additional analysis. To maintain equal sample sizes between indoor and outdoor NP measurements, 2000 random data points were obtained from indoor and outdoor measurements, respectively. The total number concentration (TNC) distributions were reviewed for normality or log-normality via probability plots and histograms. The data were found to fit better the log-normal distributions (Shapiro–Wilks test and probability plots) and were summarized using geometric means (GM) and geometric standard deviation (GSD).

Spearman correlation coefficients were calculated to assess relationship between GM TNC and variables such as dewpoint temperature, percent relative humidity, carbon monoxide, ventilation performance in cubic feet per minute (CFM), fresh air changes per hour (ACH), carbon dioxide, number of copies, number of individual print tasks, cubic volume of the copy center, and distance the workstation is from the photocopier. Correlation was considered significant at $P \leq 0.05$. Univariate linear regression analysis was conducted on significantly correlated variables, and other variables of interest, for centers with a combination of mechanical and natural ventilation only. Natural ventilated centers were excluded from regression analysis. Comparison of indoor and outdoor log TNC was performed using the Welch *t*-test for unequal variances, which has been shown reliable when comparing means of samples with unequal variance and unequal sample size (Kohr and Games, 1974; Ruxton, 2006). Welch's *t*-test was also used to compare indoor background log TNC (overnight measurements) and log TNC measured during working hours.

Results

Photocopy center environment

The design characteristics of each copy center environment are summarized in Table 1. The copy centers ranged in size from 20 to 247 m^2 (300–2665 $ft.^2$) with corresponding volumes ranging from 62 to 632 m^3 (3000–25 500 $ft.^3$), and the number of working copiers ranged from 1 to 9. Thirteen of the 15 centers relied on some form of mechanical and natural ventilation, while 2 centers relied solely on natural ventilation. Four of the 15 copy centers lacked any windows. The remaining 11 centers ranged between 2 and 11 windows, which were almost universally closed during the daily visits. Each copy center had 1 to 3 doors that were frequently in use during the course of the day to accommodate pedestrian traffic. The distance separating the workstation and the closest operating photocopier during this study ranged from ~1–3 m. The majority of the workstations (13 of 15, 87%) were positioned within 3 m of the copier and two workstations >3 m from the nearest working photocopier. The operating hours ranged from 8 to 10 h per day.

Photocopying activity and workforce

Table 1 summarizes photocopying activity and workforce observations during daily observations. The number of FTE ranged from 1 to 15. The work load from center to center varied from ~1100 to 110 000 pages day^{-1}. The number of individual print jobs ranged from 10 to 76 per day. Workers in photocopy centers rarely spend their entire day at a single workstation, and they conduct a varying number of tasks that require a low level amount of activity, such as walking to and from the service counter to copier to retrieve completed print jobs, light copier maintenance (e.g. replacing spent toner

Table 1. Physical environment of photocopy centers studied in the Northeast United States. Observations and measurements were collected during one random week day.

Center I.D.	Hours of operation per day	No. of copiers	No. of full time employees	No. of copies	No. of print jobs	Volume (m^3)	No. of doors/ windows	Workstation distance from nearest copier (m)	% Time spent at workstation
1[a]	8	2	3	109 854	35	286	1/4	3.1	75
2	8	3	3	8990	76	280	2/0	2.4	35
3	8	2	2	19 286	68	109	2/3	2.3	90
4	8	3	3	3020	43	319	1/3	1.7	50
5	8.5	3	3	1338	29	75	2/0	1.0	45
6	8	1	1	37 280	17	62	1/0	2.0	50
7	8.5	4	13	18 084	74	176	1/3	2.3	50
8[a]	8.5	9	15	56 957	68	317	3/0	0.9	50
9	10	2	8	3494	30	351	1/8	0.7	40
10	8	1	1	1094	10	138	1/2	1.1	85
11	8.5	3	2	1901	20	722	1/5	1.1	75
12	10	1	2	1378	37	255	1/2	2.0	80
13	8.5	3	3	1686	32	181	2/2	1.9	80
14	8	3	6	1085	37	528	1/2	3.5	90
15	10	3	2	2527	38	632	1/6	0.8	50

[a]Centers 1 and 2 had natural general ventilation; the rest had mechanical general ventilation.

cartridges, refilling paper bins, and staples), and other tasks away from their workstation and copiers such as document finishing (e.g. binding) and shipping. In our study, the worker was observed to spend 1–50% of the day at the copier or conducting light maintenance on the copier, 35–90% of the day at the workstation, and 0–66% of the day on other tasks. In every case, the workstation was physically in the same room as the production copiers.

Exposure controls

Emissions/exposure controls were observed only at 1 of 15 copy centers. The control(s) consisted of a loosely fitting box covering the principal emissions point of the photocopier, which we have determined in this and other work conducted by the authors to be principally the cooling exhaust (Fig. 1). Emissions flow into a three-inch flexible tube that follows, a vertical run, several 90° turns and long horizontal runs before exiting the building. We did not observe any supplementary booster pumps to aid airflow from the exhaust point of the copier to the point where the ductwork directs the emitted particles out of the building. Another emission point has been identified as the output tray, where the completed document lands after exiting the machine (Fig. 2). We did not observe controls relative to the output tray. The maximum particle measurement in this copy center approached 100 000 particles cm^{-3} at the workstation, which suggests inadequate control particle emissions.

Indoor air quality

The average carbon dioxide measurement ranged from ~792 to 1709 mg m^{-3} (440–955 ppm), which resulted in brief excursions greater than the OSHA recommended limit of 800 ppm in three copy centers. The 8-h time-weighted CO_2 average ranged from 742 to 1236 mg m^{-3} (Table 2). Estimated airflow of fresh air per person was found to be deficient in 7 of 15 centers studied here (Table 2). The ratio of the estimated airflow (Q) and the center required airflow (Q_r) must be 1.0 or greater to achieve compliance with the ASHRAE standard. Dew-point temperature ranged from ~16 to 59°F, percent relative humidity ranged from ~12 to 56% RH, meeting the ASHRAE recommended guideline of 60%, and temperature ranged from ~67 to 78°F. At each copy center, there was a slight increase in temperature measured at the workstation after copying began for the day (data not shown). Temperature was found to exceed ASHRAE guidelines in copy center #6 and copy center #8.

Total particle number

GM TNC measured at the operator's workstation ranged from ~1800 to 23 800 particles cm^{-3} with maximum particle concentrations ranging from ~4100 to 217 000 par-

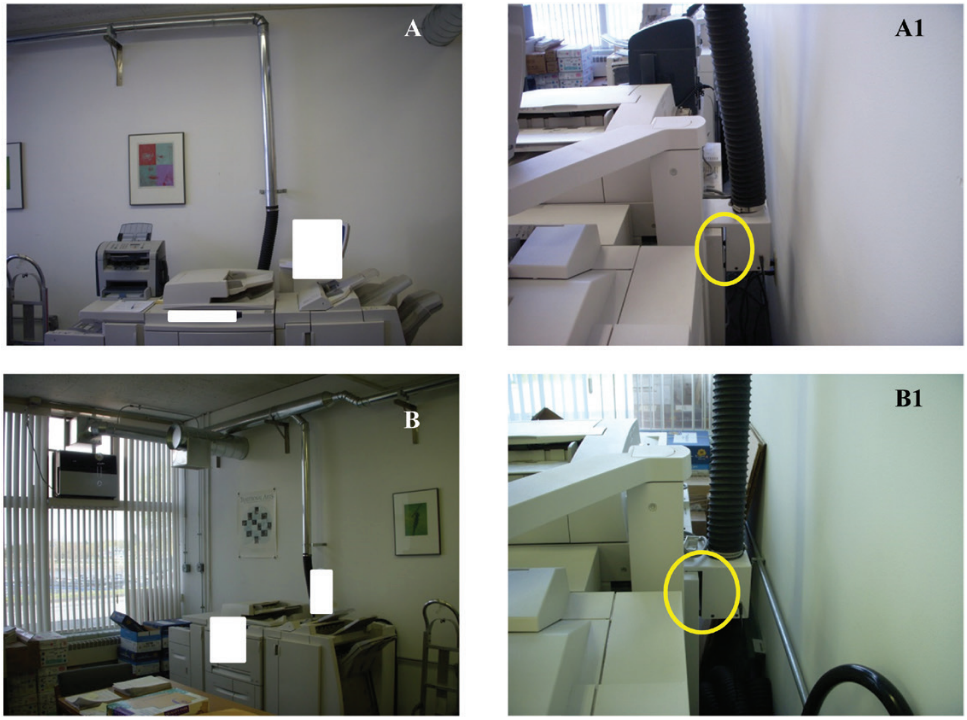

Figure 1. Emissions controls connected to the back panel of two copiers were observed at copy center #3, the only center visited with controls. As can be seen in images A and B, photocopier emissions are directed vertically away from the copier for approximately 8 feet before undergoing a near 90° turn to travel parallel to the ceiling before two more 90° turns and finally exiting the building. As can be seen in images A1 and B1, the connection to the exhaust port is not tight (circled) and the open gap may represent an emissions point. There is a 90° turn within 4 inches of leaving the copier and traveling vertically above the floor. There were no supplementary pumps or fans observed to aid the emissions away from the copier. In accordance with our agreement with the participating copy centers, any identifying markers on the copiers and in the center have been whited out.

Figure 2. Principal particle emissions points around a typical high-speed photocopier. (A) Output feeder trays and (B) cooling exhaust in the rear of the machine. Nanoparticle measurements generally show the principal particle emissions point around the photocopier is the cooling exhaust, followed by the point where documents are ejected from the machine at the output feeder tray.

ticles cm^{-1} (Table 3). In this study, we deployed the CPC at the workstation only, and did not physically follow the workers movements during the course of the day. However, the time operators spend in front of the photocopier, where NP exposure levels may be much greater than at the workstation may increase overall exposures. Overnight PM measurements were collected in 6 of 15 centers and GM TNC ranged from 2800 particles cm^{-3}

Table 2. Summary of carbon dioxide and ventilation rates at 15 commercial photocopy centers in the Northeast United States.

ID	Temperature (F) 8-h TWA	%RH 8-h TWA	CO_2 8-h TWA (mg m^{-3})	Fresh air volume (Q) (ft^3 min^{-1})[a]	Center required fresh air volume (Qr) CFM[b]	Q/Qr
1[c]	64.9	22.9	742	151	76	2.0
2	71.7	19.4	858	151	74	2.0
3	64.3	26.4	777	144	33	4.3
4	70.7	31.8	1092	60	83	0.7
5	78.5	58.0	1165	54	33	1.6
6	78.3	44.9	993	59	18	3.3
7	55.1	27.3	683	75	96	0.8
8[c]	74.1	36.5	750	257	123	2.1
9	61.6	22.2	1236	36	102	0.3
10	55.7	21.8	1091	36	34	1.1
11	43.6	12.1	1070	20	112	0.2
12	59.5	10.4	808	74	78	1.0
13	69.2	16.9	849	78	53	1.5
14	69.1	26.6	812	114	134	0.9
15	72.0	43.4	1127	51	170	0.3

Q, estimated ventilation rate; Qr, center required ventilation.
[a]Fresh air volume calculated from equation (1).
[b]Center required ventilation rate calculated based on the occupant density, area of the center (ft^2) of the copy center, and minimum ventilation rate per person recommended in the ASHRAE 62.2–2013 minimum ventilation rates guideline, calculated from equation (2).
[c]Naturally ventilated copy center.

to 8300 particles cm^{-3}. NP from overnight measurements were less than process measurements in five of six centers surveyed.

Outdoor GM TNC measurements collected on the same day ranged from GM TNC 3000 to 29 250 particles cm^{-3}. The indoor to outdoor GM TNC ratio was greater than 1.0 in 40% (6 of 15) copy centers, and ranged from a low of 0.3 in copy center #2 to a high of 4.2 in copy center #6. Welch's *t*-test results indicate all indoor GM TNC are different from outdoor GM TNC.

NP concentration is determined largely by number of pages printed

Spearman correlation coefficients (*rho*) were computed to assess the relationship between TNC measured at the workstation with temperature, % relative humidity, dewpoint temperature, air changes per hour (as measured by indoor and outdoor carbon dioxide concentrations), number of print tasks, the number of copies printed, and distance from the particle source. There was a strong positive correlation between GM TNC and the number of copies per day (*rho* = 0.72), number of copies/CFM fresh air (*rho* = 0.73), and number of copies per center volume (m^3) (*rho* = 0.71). Other, not significant correlations were calculated with respect to GM TNC: fresh air ventilation (CFM) (*rho* = −0.16), distance from the closest copier (*rho* = −0.34), %RH (*rho* = 0.439), CO_2 (*rho* = −0.211), no.of copiers (*rho* = 0.102), no. of print jobs (*rho* = 0.177), dewpoint temperature (*rho* = −0.211); number of individual print jobs (*rho* = 0.177); ACH (*rho* = 0.417); and, distance from the nearest working copier (*rho* = −0.084).

Univariate linear regression analysis suggests number of copies produced is the largest individual contributor of NP TNC among the copy centers studied here (Table 4).

Discussion

IAQ impact exposures and health

Our findings show the use of HCDs impact IAQ in the occupational environment in at least two ways. First, by introducing heat from the copy/printing process, and, second, emitting significant NP into the operators breathing zone around the copier and, as we show here, at occupants workstation.

In 66% of the cases here, we found a measurable increase in indoor temperature occurred around the time or shortly after printing jobs were submitted to photocopiers. When compared to ASHRAE Standards,

Table 3. Summary statistics of TNC of airborne particles at the operator's workstation in high volume commercial and academic photocopy centers in the Northeast United States. Measurements were collected over a minimum of six continuous hours during a random working day.

ID	Indoor copy center (day)			Outside copy center (day)		Indoor/ outdoor GM ratios (# cm^3)	Welch's *t*-test
	GM (particles cm^{-3})	GSD	Maximum (particles cm^{-3})	GM (particles cm^{-3})	GSD		
1*	22 800	1.28	39 500	10 200	1.8	2.2	3351
2*	4980	1.50	15 200	15 500	2.1	0.3	3473
3*	6 920	1.81	99 800	10 800	1.3	0.6	911
4*	8960	1.87	52 700	8500	1.5	1.1	9.8
5*	8620	2.77	64 600	14 100	1.3	0.6	442
6*	19 200	1.93	217 000	4620	1.8	4.2	5085
7*	12 000	1.39	27 300	6390	1.3	1.9	4747
8*	23 800	1.81	117 000	18 600	2.2	1.3	128
9*	10 000	1.42	24 700	29 300	1.6	0.3	7069
10*	1790	1.25	4140	27 900	1.4	0.1	105 151
11*	5950	1.50	21 000	18 500	1.5	0.3	7830
12*	7160	1.20	19 600	20 100	2.1	0.4	3645
13*	2830	1.91	66 600	3020	1.8	0.9	11.2
14*	2850	1.37	55 600	4500	1.4	0.6	2159
15*	6500	1.59	38 800	4000	1.6	1.6	1127
	Indoor copy center (day)			Indoor copy center (night)		Day/night GM ratio	
1*	22 800	1.28	39 500	2350	1.68	9.7	31 017
4*	8960	1.87	52 700	2200	1.07	4.1	7088
8*	23 800	1.81	117 000	5300	1.16	4.5	12
11*	5950	1.50	21 000	8100	1.52	0.73	986
13*	2830	1.91	66 600	1200	1.07	2.4	3040
14*	2850	1.37	55 600	1700	1.19	1.7	3595

GM, geometric mean; GSD, geometric standard deviation. The 8-h TWA is an estimate of the GM TNC exposure to the worker across the work day, taking into account time spent away from the workstation.

*Statisically significant ($P < 0.001$) difference between indoor and outdoor particle counts by Welch's *t*-test of mean and standard deviation of log concentration values.

the mean temperature measured in 13 of 15 centers was within recommended temperature range. Center #6 was a small enclosed room with no windows, and a high-speed photocopier that operated for extended periods of time with very large print jobs. Center #8 was found to be overcrowded with nine high-speed photocopiers and no mechanical HVAC system to control thermal conditions.

The GM TNC measured at the workstation in the present study, which ranged from 1800 to 23 000 particles cm^{-3}, was in general agreement with earlier studies (Lee and Hsu, 2007; Bello *et al.*, 2013; Martin *et al.*, 2015). Nightime indoor background PM measurements were found to be less than process measurements in five of six centers where such measurements were collected. We have reason to believe the one exception may have been the result of overnight cleaning that contributed to non-process inflation of NP during nonbusiness hours. These results suggest the increases in NP during business hours are caused by HCD operation.

Many factors may contribute, individually or in concert, to TNC from HCD. For example, color LPs within a controlled environmental chamber have been reported to emit greater TNC than their monochrome counterparts (Schripp *et al.*, 2009; He *et al.*, 2010). Morawska *et al.* (2009) observed a positive correlation between TNC and ozone concentrations. Paper coverage has also been reported to positively contribute to TNC (He *et al.*, 2007; Wang *et al.*, 2012; Pirela *et al.*, 2014a). Other reports are less conclusive with respect

Table 4. Univariate linear regression model summary of predictors of TNC at high-volume photocopy centers in the Greater Boston area. Each model represents a single independent univariate analysis.

Model covariates	Standardized beta coefficient	Standard error	*P*	Adjusted R^2
No. of copies	0.753	2986	0.001	0.579
No. of copies (cfm)	0.867	2398	<0.001	0.728
No. of copies (m^3)	0.791	2937	0.001	0.626
Distance of worker from machines	0.076	4791	0.806	−0.085
No. of jobs run	0.001	4805	0.997	−0.091
Center volume (m^3)	−0.325	4543	0.278	0.025
CFM fresh air	−0.188	4719	0.538	−0.052
Center floor space (m^2)	−0.335	4527	0.263	0.032
Average CO_2 (ppm)	−0.070	4793	0.821	−0.086

to paper coverage increasing TNC (Schripp *et al.*, 2008; Morawska *et al.*, 2009). Print speed has been reported to be inversely proportional to TNC (Byeon and Kim, 2012). McGarry reported decreased TNC with increasing distance from the HCD (McGarry *et al.*, 2011). In this study, we observed a slight, non significant decrease in TNC with increasing distance from 1 to 2 m from the nearest working photocopier.

In this sample of commercial photocopy centers, correlation and univariate regression analysis suggest the number of printed copies per day is the greatest contributor to TNC measured at the workstation.

Indoor NP may be affected by other indoor and outdoors sources that may inflate our findings. We did not observe other indoor NP sources in these centers (i.e. toasters, smoking, etc.), other than photocopying. Importantly, we conducted particle mapping measurements that extended into indoor areas adjacent to copy center #1. We found TNC within 3–4 m from the copy center entrance between 18 000 and 22 000 particles cm^{-3} (Fig. 3). At 8 m from the copy center entrance, TNC dropped to approximately 2800 particles cm^{-3}. This result suggests the copy center may potentially contribute to elevated NP in adjacent areas of the building. Mapping was conducted at only one center due to limited access and because eight centers were standalone. However, the results warrant additional research to assess the extent and how a copy center impacts other building areas.

We assessed indoor to outdoor (I/O) NP concentrations and found 40% of our cases have an I/O ratio of >1.0, however 53% <0.9, 33% <0.5, and 7% <0.3. Studies have shown the I/O ratio of PM concentrations vary considerably; the range for submicrometer particles has been reported from 0.3 to 0.9 (Morawska *et al.*, 2001; McAuley *et al.*, 2010; Giovanni and Mara, 2012). Ideally, I/O PM ratios should be at least one or less; the indoor environment should have fewer contaminants than the outdoor environment. Furthermore, we found the number of printed pages was the most significant correlating variable of the GM TNC in this study. Taken together, our findings of elevated TNC, elevated I/O ratios for 40% of the centers, and the strong relationship between the number of printed pages and TNC, suggest photocopying has a significant impact on IAQ at the workstation and, as documented in one center, possibly in other areas of a building.

Regulatory framework compliance

There are currently no regulations, standards, or guidelines with respect to indoor NP, irrespective of the source, in the indoor environment. Governmental agencies in the USA often adopt guidelines developed by ASHRAE to address IAQ and building related concerns. ASHRAE Standard 62.2–2013, which is designed for establishing ventilation for acceptable IAQ in numerous environments (e.g. classrooms, building lobbies, theaters, office space) briefly mentions PM as a contaminant of interest. ASHRAE 62.2–2013 suggests indoor concentrations of $PM_{2.5}$ and PM_{10} should not exceed 15 µg m^{-3} and 50 µg m^{-3}, respectively. There is no mention of NP or UFP in the document. The World Health Organization Air Quality Guidelines includes UFP, but does not establish any type of guideline that governmental agencies may review and adopt (World Health Organization—Regional Office for Europe and O. World Health, 2006). Because standards may not be enforceable their incorporation into the building codes and design of indoor spaces cannot be ensured, which may have a significant impact on PC center IAQ.

Following ASHRAE 62.2–2013, we estimated minimum ventilation rates for each space based on occupancy, space and fresh air per person requirements and compared it to the estimated ventilation measured in each center. Forty-six percent of the participating centers were inadequately ventilated on the day samples

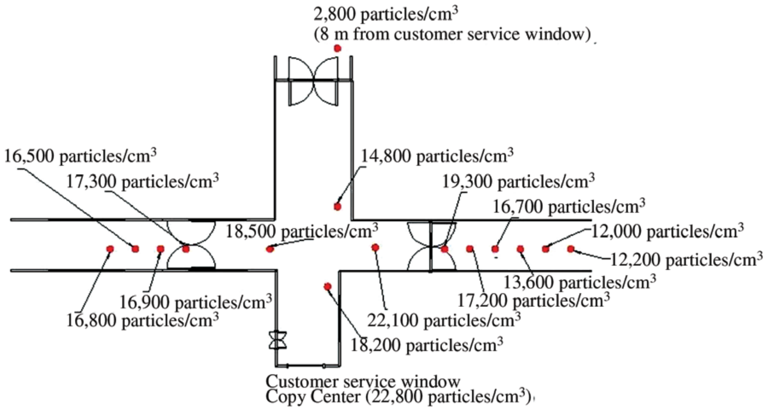

Figure 3. Particle mapping measurements collected outside and down the hallway(s) from copy center #1. Measurement point at the top of the figure is 8 m away from the customer service window. Particle measurements decrease with increasing distance from the copy center.

were collected (Table 2). Even in the centers that met or exceeded the minimum ventilation rates (e.g. centers #6 and 9), NP TNC remained quite high, with GM TNC 19000 and 10000 particles cm^{-3}, respectively. This suggests that, even when met, ASHRAE 62.2–2013 by itself may not be sufficient in reducing NP to low (near-background) levels. The growing body of toxicological literature strongly suggests exposure to HCD NPs, may result in deleterious impacts to building occupants, PC workers, patrons and the general public (Khatri et al., 2012, 2013a; Pirela et al., 2013, 2015; Sisler *et al.*, 2014). Therefore, consideration of engineered and administrative control measures, and review of NP levels in commercial copy centers is warranted, as well as in other indoor areas where HCDs operate.

Ventilation rates are important in the indoor work environment. Ventilation performance as cubic feet per minute (cfm) of fresh air per person may contribute in TNC reduction. In centers with mechanical ventilation we found a slight reduction of TNC with increasing ventilation. This finding, although not significant, warrants further study in a controlled environment. Additional data may support consideration in future editions of ASHRAE 62.2 to establish a distinct air class for the photocopy environment, including a specified airflow in and emission rates out. This, combined with engineered controls, industry modification of the PC printing technology and establishing best work practices for employees may result in a reduction of TNC at the workstation close or equal to background NP levels at the workstation. Although increasing ventilation beyond ASHRAE recommendations may aide in mitigating exposures, such an approach may not be energy or cost efficient, and other factors may have a greater influence on NP TNC. Therefore, other more efficient alternatives must be considered, as we discuss in detail in the following section. Based on our findings, there is an apparent need to raise awareness to the hazard of NPs and to maintain adequate ventilation in the photocopy environment.

Exposure control

It is apparent from our findings that engineering controls for emissions are not considered or in use at the majority of copy centers (14 of 15) we visited, and we believe this to be the norm rather than the exception within the industry. The only observed control(s) were ill-fitting 'passive' capture controls designed by the manufacturer to cover the exhaust from the copier and theoretically transfer contaminants to the outdoor space. This control design was found to be inadequate as implemented, which is supported by peak GM TNC of approximately 9.9×10^4 particles cm^{-3} measured at the workstation.

Following the hierarchy of controls described in the American National Standards Institute/American Industrial Hygiene Association (ANSI/AIHA Z10-2005, the preferred approach to mitigating a hazard begins with eliminating the hazard in favor a less toxic process or product. In the case of HCDs, simply eliminating printing is impractical due to the sheer numbers of businesses and individuals rely on HCDs for daily document production. The next option is product reformulation within the printing technology, in this case the dry toner, in favor of a substitute product that yields fewer particulate emissions. One major manufacturer has recently introduced a new source material, referred to as 'solid ink', which diverges from traditional dry toner formulations. This eliminates the need/use of dry toner, which is generally accepted as a significant source material for particle emissions in traditional copiers and printers. Our preliminary investigation of this technology suggests minimal NP emissions relative to conventional photocopying. Although such new technologies may take over in the future, thereby significantly reducing or eliminating particle exposures from the use of hardcopy devices, additional research, and comprehensive assessment of working conditions is warranted to show substituting one technology and eliminating a hazard and converting to another technology does not introduce an unforeseen hazard.

For current users, designing and implementing controls may be a more practical and cost-effective way of improving IAQ in photocopy centers, without the burden of switching to new equipment. In the absence of elimination/substitution, engineered controls represent the next best solution for hazard mitigation, followed by administrative controls or changes in work practices. The use of personal protective equipment (PPE) is the most impractical and least favorable option in the busy copy center environment. There are several broad engineered approaches to controlling emissions from photocopiers that may include (i) filtration, (ii) local exhaust ventilation (LEV), (iii) enclosures, and (iv) general exhaust ventilation (increasing fresh air ventilation rates).

The ASHRAE IAQ Guide suggests enclosing the contaminant source and therefore separating it from the rest of the indoor environment. In the case of photocopiers, this involves dedicating a room large enough to accommodate copiers and workers safely. Further, dedicated rooms should have dedicated exhaust and an administrative policy restricting workers from entering until NP TNC have been reduced to a defined threshold, or a predetermined number of air volumes have been evacuated from the room enclosure to lower the probability of worker exposure to high NP TNC. Further research is needed to guide selection of such thresholds.

Reduction of NP emissions at the source and therefore reducing TNC in the breathing zone may be achieved through careful selection and placement of filtering systems. Wensing tested retrofitted filters with a high emission LP and found TNC emission reductions ranging from 21 to 84% with respect to unfiltered emissions (Wensing *et al*., 2008). This is in good agreement with ad hoc experimental measurements conducted by the authors after retrofitting a MERV-8 mini pleated filter into an in-line filter holder on a single photocopier model (unpublished data). Because HCDs have so many shapes and sizes, a drawback to retrofitting filters to existing HCDs is a single design cannot be universally and simply applied to all HCDs. This approach may be particularly useful where the principal emissions point source is one location (i.e. exhaust); however, some studies have shown multiple emissions points. In this case, a retrofitted box filter at the exhaust would not be an effective control or would necessitate a multiple filter design. Emissions control using filtration may represent high efficiency, but may be less cost effective and more difficult to design and implement.

LEV is a well-known and widely used engineered control for welding fume and in other occupational setting such as woodworking shops, and construction operations. LEV may be fixed (i.e. a hood), or portable. Field studies show portable LEV systems can reduce welding fume and particulate exposure by 40–50% (Flynn and Susi 2012) or more, and this technology holds promise in reducing NPs in environments where HCDs are frequently used. Moreover, portable LEVs are highly maneuverable and can be positioned in optimal locations to capture emissions irrespective of the size or shape of the device, or the location of the primary emissions point on the device. LEV portability and relative low cost ($3000 USD) combined may make this an attractive control option, especially for high volume photocopy environments.

Limitations

Outside sources of NP are a constant concern with real-time particle measurements and field environments. Real-time particle measurement instruments are unable to distinguish between particles of interest and cross-contamination from other indoor particle sources (i.e. toaster ovens, microwaves, nuisance dust, and cleaning and maintenance, and particle intrusion from outdoors), which may inflate real-time particle number concentration therefore biasing the estimated exposure. We have attempted to mitigate cross-contamination by conducting a careful visual inspection of the space and noting potential sources of indoor particles, observing work practices and consumption of food items at the work space, and conducting outdoor measurements at each copy center, and where possible, indoor background measurements and particle mapping in adjacent building areas. Incomplete background measurement is a recognized limitation of this work. Additionally, we visited each participating copy center on one randomly selected day, which may have experienced an unusually high or low copy load on the day that we selected. The number of copies has been shown to highly correlate with the total particle number concentration measured both at the workstation, and in area measurements around the copier, and the workload would reflect in the particle loads measured at the workstation. By selecting and visiting the centers at random we hope these data give a representative picture of the copy center environments and highlight potential issues for further studying by the scientific community and hazard communication.

The CPC has two main limitations to this study: (i) The effective measurement range of the CPC is 0–100 000 particles cm^{-3}, which may have limited the upper end of particle measurements in this study. We have minimized coincident counting by applying TNC correction to results exceeding 100 000 particles cm^{-3}. (ii) The effective size range of detection is 20 nm to >1.0 µm, and does not size differentiate particles. We are confident CPC measured particles are <100 nm based on side-by-side FMPS measurements conducted at 8 of the 15 centers presented here. These previously reported FMPS results indicate, with few exceptions, measured particles were <100 nm (Martin *et al.*, 2015) We know for at least half of these centers, that the range of daily GM as measured by the FMPS is comparable to that measured by the CPC, but the maximum daily exposures could reach as high as 1.4×10^6 particles cm^{-3}. Therefore, it is likely that the maximum TNC values measured by the CPC may have been underestimated. Furthermore, it is well established in exposure sciences that surrogate personal sampling based on area samples almost always underestimate personal exposures. Therefore, measured NP levels at the workstation more likely underestimated true personal exposures. Particle measurements collected at the workstation may have been influenced by outside factors, but we are confident that the outside background influence does not significantly bias our end results, and therefore, our conclusions.

Conclusions

We show here that photocopying operations negatively impact the indoor environment, especially with regards to a significant increase in NP TNC in these environments, directly related to photocopying. We show our participant population of photocopy shops generally does not employ any type of particle emission capture devices to mitigate potential exposures to NP in photocopy centers. While a sizeable number of copy centers had insufficient ventilation, high exposures were documented even for cases when ASHRAE ventilation guidelines were met or exceeded. Many photocopy centers are housed in retrofitted spaces that appear to have little design consideration for work tasks performed there. In this study we observed work environment(s) that were over-crowded with multiple copiers, off-set printing presses, finishing equipment, and occupant workstations. Moreover, through our interaction with occupants during the course of this investigation it became apparent that managers, workers, and owners of photocopy shops were unaware that photocopiers emit NP in significant quantities, or that such exposure may lead to negative health effects. The high exposure levels measured in our study should not be surprising considering the heavy workload and lack of controls to mitigate emissions/exposures.

It is time to reconsider the interface of workers and consumers with this technology. Copy centers should be designed with sufficient ventilation and engineering controls should be implemented to mitigate emissions at the source. Furthermore, employees should be informed of the potential hazards of such emissions and policies (e.g. minimizing bystander exposure) implemented and enforced. Some of these issues are being addressed by ongoing research that involves comparing a substitute copying/printing technology, evaluating additional control options, and investigating the long-term health effects of HCD emitted NP.

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Conflict of Interest

The authors report no conflict of interest relevant to this work.

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