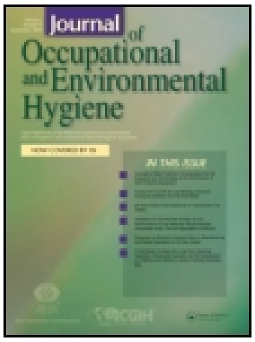

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The Effect of Worker's Location, Orientation, and Activity on Exposure

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The impact of a worker's location, orientation, and activity was studied in an experimental room (2.86 m × 2.35 m × 2.86 m) at known flow rates of 5.5 m^3/min and 3.3 m^3/min. A person in the room, wearing a full-facepiece, air-supplied respirator represented a worker. Propylene tracer gas was emitted at a constant rate from a 1-m pedestal at the center of the room and a continuous air sample was drawn from a point midway between the worker's mouth and nose. Breathing zone concentration (BZC) was monitored at 12 worker locations within the room for a stationary worker. At each location, BZCs were measured separately for four worker orientations: east, west, south, and north. BZCs of a walking worker were also monitored along the path defined by the 12 worker locations used in the stationary experiments. In a separate set of experiments, area concentration was monitored to see whether the worker's activity disturbed the contaminant concentrations at a fixed sampling point located behind the source looking from the direction of air inlet (location: 1.34 m, 1.20 m, 0.45 m). The following average differences in BZC over the 12 fixed locations were observed: 43% higher for near-field than for far-field locations; 20% higher when the worker was facing the source than when facing away (p-values for all four conditions: <0.033), and 30% higher for a moving worker than for a stationary worker (p-values for all four conditions: <0.01). When the worker was walking, the concentration at the fixed area sampling point was generally lower than the area concentration when the worker was absent or stationary in the room, possibly due to greater mixing of room air by the worker's movement. Because a worker's activities may be irregular and complicated, incorporating them as parameters in mathematical models is often not feasible. Instead, these findings may be used to assess uncertainty or adjust exposure estimates from simple models.

Keywords breathing zone concentration (BZC), moving worker, personal exposure, worker activity, worker location, worker orientation

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INTRODUCTION

A worker's exposure to airborne contaminants is a function of physical factors that affect contaminant transport within the workroom. For example, personal exposure to an airborne contaminant depends directly on the distribution pattern of the contaminant within the workroom. The distribution of contaminant concentrations, in turn, depends on the room air velocity field and the effects of source factors, such as contaminant composition, density, and generation rate. Some other factors that affect velocity and concentration fields include the type of supply air diffusers; the temperature differences between walls and room air; the room configuration; and the worker's location, orientation, and activities. These factors have an impact on the worker's exposure, but experimental investigation of the effects of all these factors and their interactions is very challenging.

Some studies have investigated the effects of fundamental physical factors on either contaminant concentrations or velocities. Those factors include room geometry,[1–7] airflow and/or room thermal characteristics,[8–11] and a worker's presence.[2,12]

The effects of a worker's orientation and activity on exposure and contaminant distribution in a room have also been studied. Brohus et al.[13] found a significant influence of persons' movements on contaminant transport in an operating room using computational fluid dynamic (CFD) simulations. Other researchers[14,15] observed higher personal exposure when the worker was facing the source and air was blowing toward the back of the worker. Also, better mixing of room air with increasing speed of a cylindrical worker surrogate was reported by several investigators.[12,16–19]

However, those studies were performed either in a wind tunnel[14,15] or in a room with displacement ventilation,[12,16–19] not workrooms with dilution ventilation as are most common in North America. Wind tunnel studies are valuable for investigating the effects of uniform air velocity on exposure but represent extreme effects of airflow relative to the effects of airflow in a workroom with dilution ventilation. Where exposure is controlled by dilution ventilation, the room is mixed to some degree in that the air speed and direction vary much more than in a wind tunnel. Dilution ventilation also differs markedly from displacement ventilation.

In displacement ventilation, supply air is introduced at a low inlet velocity near floor level, and contaminant emissions that are warmer than the surrounding room air rise toward the ceiling, where they are removed from the room in exhaust air. In addition to low velocity at the supply inlet, the thermal characteristics of the room are controlled to produce a stable vertical temperature structure (density decreases from floor to ceiling) suppressing air mixing by natural convection. In dilution ventilation, room airflow is driven by the inertia of the supply air blowing into the room and sometimes by fans inside the room. These flows produce turbulence and circulation within the room, which enhance mixing.

Because most previous studies of the effects of worker factors (such as location, orientation, and activity) on exposure were performed in wind tunnels and displacement ventilation, which differ substantially from dilution-ventilated rooms, research on these factors in dilution ventilation is needed. Also, previous studies of a moving worker restricted the worker's movement to a single dimension, back and forth in the middle of room, not walking around a room. Therefore, the primary objective of this study was to investigate the effect of worker's location, orientation, and activity on breathing zone concentration (BZC) of a gaseous contaminant in a room with dilution ventilation. Because a moving worker may affect the exposure in another part of the room, a second objective was to determine the effect of a moving worker on contaminant concentration at a fixed area sampling location in the room with dilution ventilation.

This study was part of a larger project whose long-term goal was to improve methods for estimating exposure by exploring the impact of some of the fundamental physical factors that affect worker's exposure in a dilution-ventilated workroom. In addition to studying the effects of worker's location, orientation, and activity presented here, the larger project explored the effects of other factors on the distribution of contaminants within a workroom; those other factors are dilution airflow rate, differences between room air and wall temperatures,[20] supply air inlet type,[21] and a worker's location.[22]

METHODS

Experimental Setup

The experimental room for simulating contaminant transport and exposure in workrooms was placed within a thermostatically controlled laboratory room. To simulate work rooms somewhat larger than the space available, the experimental parameters were set based on similarity criteria. In geometrically similar spaces (for example, a 1 × 2 × 3 meter space is similar to a 2 × 4 × 6 meter space), airflow patterns are similar when the ratios of all the forces that affect fluid motion are equal.[23] When a room's physical dimensions are increased proportionally in all three dimensions for isothermal conditions, the airflow patterns within the room will also change proportionally if the Reynolds number (Re) is kept constant.

$$\mathrm{Re} = \frac{ux\rho}{\mu}$$

where u = air velocity, x = a characteristic physical dimension, ρ = gas density, and μ = gas viscosity.

Re is the ratio of inertial forces ($u\rho$) to viscous forces (μ/x). For constant temperature and pressure, both gas density and viscosity are constant. Re may be held constant by keeping the product of u and x constant. Thus, if the physical dimensions of a room are increased by a scaling factor of S, to keep Re constant the dilution airflow rate must also be increased by a factor of S. For this example, the volume of the room changes by a factor of S^3. Therefore, the air change rate (Q/V) is decreased by a factor of S^{-2}.

The experimental room (Figure 1) was 2.86 m (L) × 2.86 m (W) × 2.35 m (H), with a volume of 19 m^3 equivalent to larger workrooms. For instance, the velocity pattern for experimental conditions of Q = 3.3 m^3/min and 10.3 air changes per hour (ACH) is similar to a room six times larger in all dimensions at Q = 19.8 m^3/min. Such a room has a volume of 4152 m^3 and a normalized flow rate of 0.29 ACH. (Similarity criteria are discussed in greater detail in the Appendix).

The room was constructed with plywood on the interior walls, and the exterior was insulated with a rigid foam/aluminum foil laminate (Rmax-plus), with a 1-m high source pedestal, a dilution air inlet, and a room air exhaust to the outside. The interior surface of the plywood was coated with Teflon paint to prevent chemical sorption by the surface. The source pedestal had a small opening in the upper

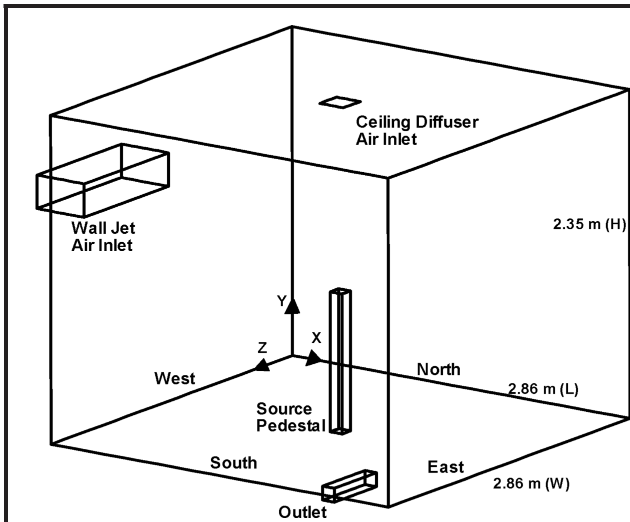

FIGURE 1. Experimental workroom

surface with a windscreen (diameter = 0.1 m) through which a tracer gas was discharged into the room. The 1 meter height was chosen because it is nearly midway between two recommended heights for a standing workplace[(24)] (107 cm for light assembly, writing, and packing tasks, and 91 cm for tasks requiring large downward or sideward forces).

Room air was supplied by either a wall jet (WJ) air inlet or a ceiling diffuser (CD) air inlet with a common exhaust outlet. The jet from the wall inlet is near the ceiling and parallel to it. The CD jet also was directed along the ceiling by several turning vanes in the diffuser. Both jets, though expanding somewhat with distance from the inlets, maintained some attachment to the ceiling by the Coanda effect. The measured air speeds in the occupied zone did not exceed the recommended comfort limit of 18 m/min.[(23,25)] The dimensions and positions of object centers are listed in Table I.

A centrifugal fan located outside the building exhausted room air through the outlet of the experimental room at known flow rates of 5.5 m^3/min (17.2 ACH) and 3.3 m^3/min (10.2 ACH), drawing clean air into the room. The room was tested for leakage by comparing airflow rates at the inlet and the exhaust. In addition, velocities in the exhaust duct were measured before and after experiments to ensure a constant airflow rate by obtaining velocity along two perpendicular six-point traverses across a 4-inch diameter exhaust duct with a thermoanemometer (model 8350 VelociCalc; TSI Inc., St. Paul, Minn.).

A photoionization analyzer (PID 101; Process Analyzers, Walpole, Mass.) was used to measure BZC. For quality assurance, the PI analyzer was calibrated before and after each experiment using a known concentration of propylene (100 ppm) in a Tedlar bag. The analyzer was connected to a data logger (StowAway Volt; Onset Computer Corp., Pocasset, Mass.) to record readings every other second.

Pure propylene (99.5%) was used as a tracer to represent a gaseous contaminant. It was bled from a compressed gas tank at constant pressure through a calibrated rotameter and continuously injected at 200 cm^3/min for the 5.5 m^3/min airflow and 150 cm^3/min for the 3.3 m^3/min airflow. Different tracer emission rates were applied to keep tracer concentrations within the optimal range for measurement with the PI analyzer. Also, pure propylene was selected as the tracer gas because it is easily measured using the PI analyzer, is relatively nonreactive at the level of oxidizers commonly found in indoor and outdoor air and is nontoxic at the concentrations observed.

To promote a uniform distribution of tracer across the opening, tracer was discharged through a fine screen in the opening on top of the source pedestal. The room was allowed to equilibrate for 2 hours at constant air and tracer gas flow rates to achieve steady-state conditions before monitoring began. Three replicate sets of measurements were taken on different days for each combination of experimental variables: two inlet types and two airflow rates.

TABLE I. Dimensions and Coordinates of Object Center

Object	Size (m)	Position (x, y, z) (m)
Air inlet		
Wall jet	0.39 (L) × 0.24 (H)	0.81, 2.12, 2.86
Ceiling diffuser	0.28 (L) × 0.28 (W)	1.43, 2.35, 1.43
Exhaust	D = 0.1	2.71, 0.18, 2.86
Source pedestal	0.1 (ID) × 1.0 (H)	1.43, 1.00, 1.43

Worker's Orientations and Movements

A person in the room, wearing a full facepiece, air-supplied respirator (Neoterik Health Technologies, Inc., Woodsboro, Md.), represented a stationary worker and a moving worker. Procedures involving a human subject were reviewed and approved by the University of South Carolina Institutional Review Board (IRB) before measuring BZCs.

After achieving steady-state conditions, the worker entered the room and the entrance was sealed with tape. An additional waiting period of 20–25 min was used to reach steady-state conditions.

For the stationary worker experiments, BZCs of the standing worker were measured at 12 sampling locations and four worker orientations (i.e., east, west, south, and north) at each location (Figure 2). These experiments were performed (*a*) to determine the ratio of BZCs in the near-field of the source to those in the far-field, and (*b*) to investigate the effect of the worker's orientation on BZC.

A total of 12 sampling locations were selected to compare average concentrations of near and far for each condition investigated. The far-field was sampling points 1–8; near-field was sampling points 9–12. In previous studies, defining near-field and far-field has been somewhat arbitrary. Near-field has been defined as a volume of 8 m^3surrounding a worker,[(26,27)] a 1 meter distance from a worker,[(28,29)] and a 1 meter radius hemisphere centering at the source.[(30)] Far-field is generally defined as the rest of the area or volume outside the near-field. In this study, the near- and far-field distance was smaller than in previous studies because of a smaller room size than was used in previous studies above. For example, room volumes in previous studies were in the range of 38–3008 m^3[(26)] and 210 m^3,[(30)] which are 2–158 times larger than the room size in the present study.

Worker orientations at each sampling point were categorized in three groups: facing toward the source (FT), facing away from the source (FA), and sideways to the source (S), that is, one shoulder was toward the source. Two orientations, the south and north at sampling points 2 and 6, and the east and west at the sampling points 4 and 8, make up the sideways orientation groups (see Figure 2). At each orientation for each sampling point, BZCs were monitored for 1 min. After each change of orientation, 1 min was allowed for flushing out the sampling tube. The estimated average residence time in the sampling tube was less than 10 sec.

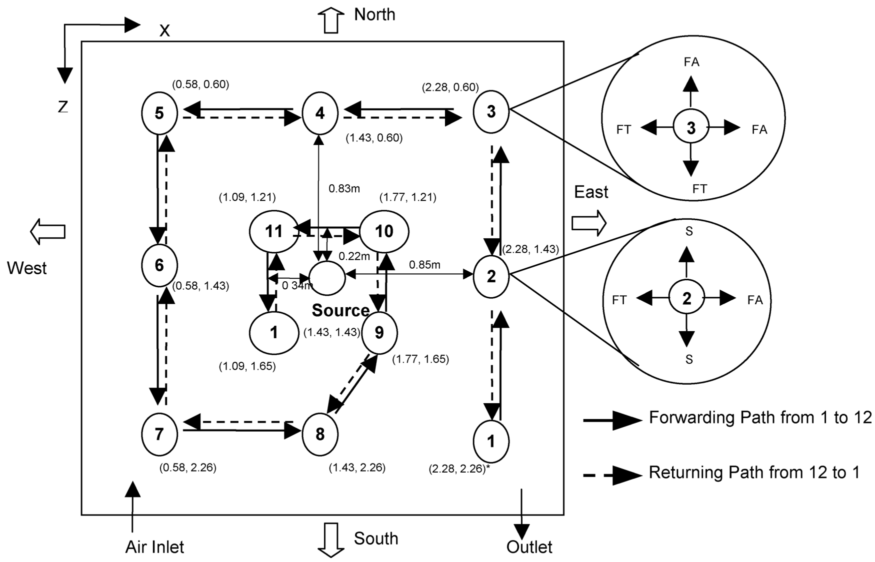

FIGURE 2. Numbered sampling points for a stationary worker and the path of a moving worker (a human being was used in the experiment). Note: * = sampling location given in the room coordinate system (X, Z); Worker orientation: FT = facing toward the source, FA = facing away from the source, and S = sideways to the source.

For the moving worker experiments, the worker walked continuously along the path defined by the 12 numbered sampling points (Figure 2) for 3 min. After the worker walked along the path from point 1 to point 12 (solid line in Figure 2), the worker returned back from point 12 to point 1 (dotted line in Figure 2). Consistent paths were employed through the numbered points to allow comparison of BZCs for a moving worker with that of stationary workers. The pace of worker movement was also monitored and kept consistent for all experiments.

For each condition, a continuous sample was drawn through a length of 1/16-inch tubing (Tygon) with the open end positioned in front of the respirator, between mouth and nose (height: 1.6 m), to obtain BZCs. Preliminary tests showed no influence of relatively clean air coming out from the bottom of the respirator on the tracer gas concentration in the breathing zone. Three replicates of experiments on different days were performed. However, because of instrument malfunction during experiments at 5.5 m^3/min/WJ condition, the results of only two experiments were reported for this condition. Three replicate experimental results were reported for other conditions.

Comparison of Area Concentrations at the Fixed Area Sampling Point

In a separate set of experiments, tests were performed to see whether a worker's activity disturbed the average contaminant concentration at a randomly selected, area sampling point (location (X, Y, Z): 1.34 m, 1.20 m, 0.45 m). The worker walked along the path described above and shown in Figure 2. For both flow rates/WJ conditions, area monitoring results with a moving worker in the room were compared with area monitoring results, published previously,[22] at the same point with a stationary worker present. In the previous study, the stationary worker was represented by a heated mannequin (120 W). Figure 3 shows locations of the mannequin in the room and the fixed area sampling point.

Analysis

Average absolute percent error occurring from three replicates of experiments was calculated for the effect of worker's

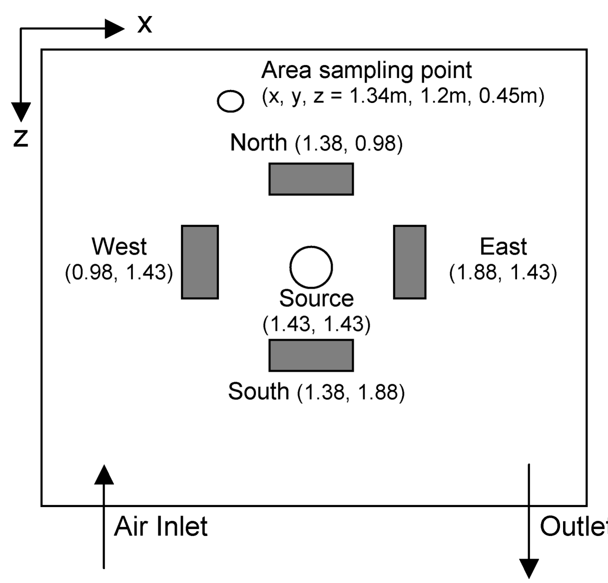

FIGURE 3. Locations of the heated mannequin (120 W) and the fixed area sampling point. The gray boxes indicate locations of the heated mannequin given in the room coordinate system (x, z).

orientation. The following equation was used:

$$\text{Average abs \% error} = \frac{\sum_{x=1}^{x=3} \frac{|C_{i,x} - C_{avg}|}{C_{avg}} \times 100}{3}$$

where $C_{i,x}$ = time weighted average (TWA)-BZC at sampling point i for the number of replicates, x (x = 1–3), and C_{avg} = average TWA-BZC of three replicates at sampling point i.

Statistical tests were performed for quantitative comparisons using the statistical software package SAS v 9.1. Paired t-tests were performed for the effect of worker's orientations with respect to the source. The hypothesis was that there was no significant difference between BZCs when the worker was facing toward and when facing away from the source (H_o: BZC_{FTi} = BZC_{FAi}, where BZC_{FT} = TWA-BZC as the worker faced toward the source, BZC_{FA} = TWA-BZC as the worker faced away from the source, and i = number of sampling location).

For the effect of worker's activity, one-way analysis of variance (ANOVA) was conducted to determine whether there was any significant difference between the overall BZC of the stationary worker and the BZC for the worker walking along the path (Ho: BZC_{SW} = BZC_{MW}, where BZC_{SW} = average BZC when the worker was stationary at 12 location [Figure 2], and BZC_{MW} = average BZC when the worker was walking along the path).

Area concentrations for varying conditions of worker's activity were analyzed by one-way ANOVA test to determine whether any significant differences existed among average area concentrations for all conditions investigated (H_o: C_{MW} = C_{NW} = C_{WE} = C_{WW} = C_{WS} = C_{WN}, where C_{MW} = average area concentration when the worker was walking along the path; C_{NW} = average area concentration when no worker was present; and $C_{WE,WW,WS,\ and\ WN}$ = average area concentration when the heated mannequin was present east, west, south, and north of the source, respectively). For the individual comparison, multiple comparison procedures, using Scheffe's adjustment, were performed to determine where the differences lay. A significance level of $\alpha = 0.05$ was used for all analyses.

RESULTS AND DISCUSSION

Effect of Worker's Location

As shown in Table II, the overall average concentration near the source (sampling points 9, 10, 11, and 12) was higher than the overall average concentration far from the source as anticipated. The ratio of overall average concentration between near and far from the source ranged from 1.33 to 1.60. Better mixing of room air was observed in the far-field, showing lower coefficients of variation (CVs) than the CVs in the near-field. Higher concentration gradients were observed in the near-field.

A similar study was performed by Cherrie,[26] who simulated exposure levels using a box model with a source in the near-field by employing factorial combinations of five far-field volumes, five air exchange rates between the far-field and outside the room, and three air exchange rates from the near-field to the far-field. Cherrie reported the results in four categories, factorial combination of two room sizes: small ($\leq$100 m^3) and large ($\geq$1000 m^3); and two ventilation rates, good ($\geq$10 ACH) and poor ($\leq$1 ACH). The experimental room described here falls in the small room/good ventilation category ($\leq$100 m^3 and $\geq$10 ACH). The range of near-field to far-field concentration ratios measured in the current study (1.33–1.60) was in the lower portion of the range 1.20–5.56 estimated by Cherrie.[26]

Effect of Worker's Orientation

Table III shows average absolute percent error occurring from three replicates of experiments; for 5.5 m^3/min/WJ condition, only two replicates of experiments were reported due to anomalies in the data from one experiment at this

TABLE II. Overall Average Concentration and CV Near and Far from Source

Inlet type/ Flow Rate	Average Concentration (ppm) Near[B]	Average Concentration (ppm) Far[C]	Coefficient of Variation (CV)[A] Near	Coefficient of Variation (CV)[A] Far	Ratio of Concentration (Near/Far)
Wall jet					
5.5 m^3/min	59.9	37.4	0.22	0.14	1.60
3.3 m^3/min	69.8	52.5	0.21	0.13	1.33
Ceiling Diffuser					
5.5 m^3/min	42.7	30.6	0.36	0.05	1.40
3.3 m^3/min	56.8	40.7	0.27	0.14	1.40

[A] Coefficient of variation (CV) = standard deviation (SD) / average concentration.
[B] Overall average concentration of 4 sampling points nearest the source. Horizontal and vertical distance from the center of the source was 34 cm and 22 cm, respectively (sampling points from 9 to 12, Figure 2).
[C] Overall average concentration of 8 sampling points farthest from the source. Horizontal and vertical distance from the center of the source was 85 cm and 83 cm, respectively (sampling points from 1 to 8, Figure 2).

TABLE III. Average Absolute Percent Error

Orientation	Flow Rate/Inlet type: 5.5 m^3/min/WJ[A]	5.5 m^3/min/CD	3.3 m^3/min/WJ	3.3 m^3/min/CD
East	12.6	7.9–8.7	15.0–25.5	16.9–33.1
West	5.1	8.9–14.6	11.4–14.4	14.7–28.2
South	5.0	10.1–16.7	12.1–18.1	13.3–23.1
North	9.4	7.3–11.7	13.3–19.5	14.4–23.6
Average[B]	8.0	10.7	15.6	20.1

[A] Only two replicates of experiments were reported due to anomalies in the data from one experiment at this condition.
[B] Overall average absolute percent error for all orientations.

condition. Overall, average absolute percent errors for WJ conditions showed less variation than those for CD conditions for both flowrates.

As shown in Tables IV and V, BZCs when facing toward the source at each sampling point were higher (FT/FA ratio: 1.15–1.25 for 37 out of 48 sampling points) or nearly the same (FT/FA ratio: 0.89–0.99 for 9 out of 48 sampling points) than those when the worker was facing away from the source. Statistical tests also detected that exposures were significantly higher when the worker was facing toward the source than when facing away from the source for all positions analyzed (p-values for four conditions: <0.033). For the WJ air inlet, sampling points 11 and 12 for 5.5 m^3/min and sampling points 10 and 11 for 3.3 m^3/min showed the largest differences; these sampling points were located near the source, an area with high concentration gradients. The same pattern was observed for the CD air inlet where large differences were observed at all sampling points near the source.

Interesting results were observed when the worker was oriented with the side of his body toward the source. For both flow rates/WJ condition, BZCs for sideways orientation at sampling points 4 and 6 were higher than FT and FA orientations at those sampling points. Also, for 3.3 m^3/min/CD condition, BZCs for all sideways orientations were higher than measured BZCs for FT and FA. Explanation of this phenomenon is very complicated because of unpredictable flow directions in the room, unlike unidirectional flow in a wind tunnel.

Previous studies by Hyun and Kleinstreuer[14] and Welling et al.[15] came to the same conclusions but presented very

TABLE IV. Breathing Zone Concentrations and Statistical Test Results (5.5 m^3/min)

Sampling Point	Wall Jet Air Inlet: FT	FA	S	FT/FA	Ceiling Diffuser Air Inlet: FT	FA	S	FT/FA
1	22.7	20.3	—	1.12	34.0	35.8	—	0.95
2	31.0	25.9	31.5	1.20	28.7	27.8	27.8	1.03
3	43.0	41.5	—	1.04	31.1	33.9	—	0.92
4	46.0	43.4	51.1	1.06	28.4	25.9	28.1	1.10
5	49.5	38.6	—	1.28	31.0	31.3	—	0.99
6	26.0	27.5	50.2	0.94	31.0	29.4	29.9	1.05
7	34.4	32.4	—	1.06	30.4	29.2	—	1.04
8	46.8	35.8	42.4	1.31	35.4	27.5	30.0	1.29
9	66.6	54.4	—	1.22	54.7	34.4	—	1.59
10	56.2	52.0	—	1.08	52.0	34.3	—	1.52
11	63.7	48.4	—	1.32	47.5	34.6	—	1.37
12	83.8	54.3	—	1.54	58.5	25.8	—	2.26
Average	47.5	39.6	—	1.20	38.6	30.8	—	1.25
Paired t-test (p-value)		0.0083				0.0329		

Notes: FT = facing toward; FA = facing away; S = source. Paired t-test was performed to detect any statistical difference between BZCs when facing toward and facing away from the source.

TABLE V. Breathing Zone Concentrations and Statistical Test Results (3.3 m³/min)

Sampling Point	Experimental Condition: Wall Jet Air Inlet FT	FA	S	FT/FA	Ceiling Diffuser Air Inlet FT	FA	S	FT/FA
1	61.8	48.7	—	1.27	45.5	34.9	—	1.31
2	52.3	58.7	57.4	0.89	42.4	45.5	50.8	0.93
3	66.7	59.4	—	1.12	42.5	46.3	—	0.92
4	60.5	55.9	71.4	1.08	34.3	35.5	40.4	0.97
5	32.4	34.5	—	0.94	33.7	32.6	—	1.03
6	50.5	46.9	52.9	1.08	41.5	34.8	50.2	1.19
7	42.1	34.9	—	1.20	43.3	36.1	—	1.20
8	68.5	49.9	55.7	1.37	36.3	29.9	44.2	1.22
9	66.7	65.6	—	1.02	62.7	54.9	—	1.14
10	71.2	53.2	—	1.34	67.1	42.9	—	1.56
11	91.1	66.5	—	1.37	63.9	45.3	—	1.41
12	76.7	66.9	—	1.15	72.7	44.9	—	1.62
Average	61.7	53.4	—	1.15	48.8	40.3	—	1.21
Paired t-test (p-value)		0.0092				0.0154		

Notes: FT = facing toward; FA = facing away; S = source. Paired t-test was performed to detect any statistical difference between BZCs when facing toward and facing away from the source.

different ratios. Hyun and Kleinstreuer[14] concluded that when a heated mannequin faced toward the source with a breathing zone height of 1.6 m and air blowing toward the back of the mannequin at a velocity of 0.15 m/s, the steady-state personal dose was about 22 times greater than the dose when the mannequin faced away from the source and into the airflow.

Welling et al.[15] measured the mean concentration of vaporized acetone at a height of 0.94 m and a distance of 0.35 m at nose level with freestream velocity of 0.3 m/s in a wind tunnel. A worker, represented by a 1.75-m mannequin, was positioned in three different orientations, with air flowing from behind, front, and side. They found that mean acetone concentrations with freestream flow from behind of the mannequin were 126 and 57.5 times greater than the mean acetone concentration with freestream flow from in front.

Both studies[14,15] were conducted in unidirectional turbulent flow in a wind tunnel, and discrepancies between the two studies are probably due to different velocities and source locations. In the current study, the worker's orientation had a smaller but still significant effect on BZC in the experimental room more realistically representing a typical workroom.

Effect of Worker's Movement

As shown in Table VI, TWA exposure for the moving worker was consistently higher, ranging from 1.14 to 1.51 times greater than TWA exposure for the stationary worker standing still at designated stopping points. Statistical tests also showed the same result from those comparisons (p-values for all four conditions: <0.01).

Previous experimental results[2,12,19] indicated that disruption of convective flow along the front of a moving worker had an important effect on exposure. In a room using displacement ventilation with a stationary, heated mannequin, clean air from lower parts of the room was transported up along the surface of the mannequin due to natural convection.

TABLE VI. Comparison of TWA Breathing Zone Concentration

Condition	5.5 m³/min WJ Inlet	5.5 m³/min CD Inlet	3.3 m³/min WJ Inlet	3.3 m³/min CD Inlet
Stationary worker[A] (ppm)	44.9	34.6	58.2	46.0
Moving worker[B] (ppm)	56.1	52.3	66.1	61.7
Ratio[C]	1.25	1.51	1.14	1.34
F-test statistics (p-value)[D]	14.12	24.62	7.10	30.92
	(0.0002)	(<0.0001)	(0.0081)	(<0.0001)

Notes: CD=ceiling diffuser ; WJ=wall jet.
[A] The overall average concentration of 12 sampling points for a stationary worker.
[B] The overall average concentration walking path defined by the 12 sampling points for 3 min.
[C] Ratio = time-weighted average (TWA) exposure of the moving worker/TWA exposure of the stationary worker.
[D] From one-way ANOVA test.

TABLE VII. Average Area Concentrations of Worker's Activity at a Randomly Selected Sampling Point

5.5 m^3/min			3.3 m^3/min		
Condition[A]	Concentration[B] (ppm)	Individual Comparison[C]	Condition[A]	Concentration[B] (ppm)	Individual Comparison[C]
WS	40.8	A	WS	54.7	A
WN	41.7	A	MW	50.6	A
MW	45.1	A	NW	68.6	B
WW	51.5	B	WN	69.8	B
NW	52.6	C B	WE	83.2	C
WE	56.0	C	WW	89.2	C
	F-Test statistics (p-value):[D] 54.5 (<0.0001)			F-Test statistics (p-value):[D] 107.2 (<0.0001)	

Notes: Sampling point (location ((x, y, z) = 1.3 m, 1.2 m, 0.5 m) (WJ inlet).
[A]Conditions of worker's activity: MW = moving worker; NW = No worker or mannequin present; WE, WW, WS, and WN = heated mannequin present east, west, south, and north of the source, respectively.
[B]Time-weighted average concentration at the fixed sampling point for each condition.
[C]Same letters indicate that the difference of concentrations was not significant.
[D]From one-way ANOVA test.

However, when the mannequin was moved back and forth, the effectiveness of entrainment of clean air in the mannequin's boundary layer (the thermal convective flow layer generated from the difference between body temperature and room air temperature) decreased, resulting in higher personal exposure for a moving mannequin than for a stationary mannequin, either sitting or standing. In the current study, the same result was observed in a room with dilution ventilation; when the worker walked along the path, the natural convection boundary layer along the front of the worker was disrupted, allowing room air at breathing zone height to penetrate to the breathing zone.

Comparison of Area Concentrations for Varying Conditions of a Worker's Activity

Table VII reports the TWA concentrations at the fixed area sampling point, ((x, y, z) = 1.3 m, 1.2 m, 0.5 m) for varying conditions of a worker's activity and locations. For both flow rates and when the worker was walking along the path, the area monitoring result was generally lower than or almost equal to results for other conditions. The shortest distance from the worker's path to the fixed sampling point was 15 cm. The worker's movement probably disrupted the room airflow and generated more mixing of room air, causing lower concentration at the sampling point. Presumably, when the worker was absent or standing still, incomplete mixing of room air generated locally lower or dead air space at the sampling point and thus promoted higher concentrations at that specific point.

Overall, statistically significant results were detected from comparisons of area concentrations for varying conditions of the worker's activity. Overall p-values for both flow rates were less than 0.0001. Individual comparisons were performed with multiple comparison procedures, using Scheffe's adjustment, to determine where the differences were. As shown in Table VII, no statistical significance was detected from the comparison of WW vs. NW, NW vs. WE, and WS vs. WN vs. MW for 5.5m^3/min and the comparison of WS vs. MW, NW vs. WN, and WE vs. WW for 3.3 m^3/min.

CONCLUSIONS

Breathing zone concentrations of the stationary worker were monitored at various locations and four orientations at each location. In this study, the average BZC was higher in the near-field of the source than in the far-field because of higher concentration gradients in the near field. The experimental results also demonstrated that the worker was likely to have higher exposures when facing toward the source than when facing away from the source. BZC of the worker walking along the path connecting the 12 sampling points within the room was significantly higher than BZC of the worker standing still at these points along the path. This might have happened because motion disrupted the vertical convective flow around the body of the moving worker at low air speeds as observed by other researchers.[(2)] Also, when the worker walked along the path, the average area concentration at the fixed sampling point was generally lower than when the worker was absent or stationary in the room. Presumably, the worker's movement generated locally better mixing of room air at that specific location. However, this conclusion applies to the single monitoring location and cannot be assumed to represent concentrations throughout the experimental room.

The outcomes for conditions studied here are: the average ratio of BZC in the near-field vs. far-field was 1.43 (ranging from 1.33 to 1.60); of facing toward the source vs. facing away from the source was 1.20 (ranging from 0.89 to 2.26);

and for the moving worker vs. the stationary worker was 1.30 (ranging from 1.13 to 1.51). These ratios indicate that personal exposure is not just a function of one characteristic. Findings from this investigation indicate that a worker's activity in a room should be taken into account when estimating BZC mathematically[26,31–33] or computationally[34] in epidemiologic studies. For example, BZC estimation of a worker facing toward a source might be underestimated if the worker's orientation is not considered. One reason for underestimating the true concentration would be that most exposure assessment models do not explicitly account for other characteristics of the work environment that may affect exposure. Therefore, inclusion of a worker's orientation and activity in these models would likely increase accuracy and precision of exposure estimates. However, treatment of those factors investigated here as distinct model parameters is not feasible in most cases because workers' activities are often irregular and complicated. Instead, these findings may be used to assess uncertainty or adjust exposure estimates from simple models. For example, a model estimate multiplied by the average ratio of worker's movement and standing still promises a more accurate estimate than the model estimate itself. However, differences between an actual workroom and the one studied here must be carefully considered before applying these ratios. One important difference could be the elevation of the source and/or density differences between the emissions and the surrounding room air. In this study, the emission height was about 1.0 m, which is about 0.6 m below the breathing zone. Further studies are needed to investigate the range of these ratios for various workroom conditions not explored in the present study.

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APPENDIX

Application of Similarity Criteria

Similarity criteria may be used to extend results of these experiments to larger workrooms with lower air change rates. The rooms to which these results apply must be geometrically similar, that is, they must have the same shape, although larger. In such rooms under isothermal conditions, it is then possible to specify a dilution airflow rate and, thus, an air change rate that will produce a velocity field and a concentration field with the same shape as these fields in the experimental room, although larger and in proposition to the size of the room. This condition is called kinematic similarity.

In geometrically similar spaces, kinematic similarity occurs when the ratios of all the forces that affect fluid motion are equal. When a room's physical dimensions are increased proportionally in all three dimensions, the airflow patterns within a room will also change proportionally if the Reynolds number (Re) is kept constant.

$$\mathrm{Re} = \frac{\mathrm{ux}\rho}{\mu}$$

where u = air velocity, x = a characteristic physical dimension, ρ = gas density, and μ = gas viscosity. Re is the ratio of inertial forces (uρ) to viscous forces (μ/x).

For constant temperature and pressure, both gas density and viscosity are constant. Thus, Re may be held constant by keeping the product of u and x constant. Using the subscript "o" to indicate the room parameter used here, and the subscript "i" to indicate some other set of parameters, the condition of constant Re yields:

$$u_i x_i = u_0 x_0$$

Let a scaling factor, $S = x_i/x_o$, Q = the volumetric flow rate of air into the room, A = the cross-sectional area of the room, and u = Q/A. If all three dimensions of the room are changed by a factor of S, then by substitution it may be shown that Re will be unchanged if Q is changed by a factor of S also. Thus,

$$Q_i = SQ_o$$

The new room is also larger in volume:

$$V_i = S^3 V_o$$

Letting the air change rate per hour, ACH = Q/V, then:

$$\mathrm{ACH}_i = \frac{\mathrm{ACH}_o}{S^2}$$

					$Q_o = 3.3$ m^3/min					
S	1	2	3	4	5	6	7	8	9	10
A (m^2)	8	33	74	131	204	294	401	523	663	818
V (m^3)	19	154	519	1230	2403	4152	6593	9842	14013	19222
Q_i (m^3/min)	3.3	6.6	9.9	13.2	16.5	19.8	23.1	26.4	29.7	33.0
ACH_i (hr)	10.30	2.57	1.14	0.64	0.41	0.29	0.21	0.16	0.13	0.10
					$Q_o = 5.5$ m^3/min					
S	1	2	3	4	5	6	7	8	9	10
A (m^2)	8	33	74	131	204	294	401	523	663	818
V (m^3)	19	154	519	1230	2403	4152	6593	9842	14013	19222
Q_i (m^3/min)	5.5	11.0	16.5	22.0	27.5	33.0	38.5	44.0	49.5	55.0
ACH_i (hr)	17.17	4.29	1.91	1.07	0.69	0.48	0.35	0.27	0.21	0.17

Johnson[(A2)] presented ACH as a log-normal distribution in various nonresidential and nonschool microenvironments. The geometric mean was 1.23 with a geometric standard deviation of 1.93. Air change rates of 0.34 ACH and 4.50 represent the 2.5th and the 97.5th percentiles of the distribution.

Thus, increasing the three linear dimensions and the volumetric flow rate by a factor of S keeps the Re constant and gives a similar airflow pattern but a much smaller air change rat.(A1)

For scale factors of 1 up to 10, Table AI shows the increase in volume, as well as the required Q, computed by Excel Solver, to give the same Re as the experimental room.

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