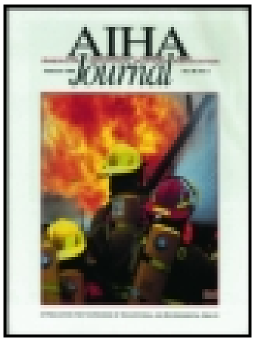

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Air Sampling at the Chest and Ear as Representative of the Breathing Zone

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Air Sampling at the Chest and Ear as Representative of the Breathing Zone

Tracer gas concentrations were measured on a 60%-sized mannequin holding a pure sulfur hexafluoride source in its hands at waist height while it stood in a wind tunnel. Samplers were placed at the mannequin's mouth, in front of the ear, and at three chest locations at lapel level. Simultaneous 15-min time-weighted average samples were taken by drawing air into different sampling bags with sampling pumps. For the factorial study design, test conditions included cross-draft velocities of 10, 22, 47, and 80 ft/min; three mannequin orientations (facing to, side to, and back to cross-draft), and rotating speed through an 80° arc (fast, slow, and no movement). Each study condition was tested twice. Concentrations at all sampling locations when the mannequin faced to the front and side were less than a tenth of the levels measured at the nose (C_{nose}) when the mannequin faced downstream. Higher velocities significantly increased concentration at the Back orientation and generally reduced it at the Side and Facing orientations. Concentrations at the nose were different from concentrations at other sites. For 34 of 36 samples the mean chest concentration (C_{chest}) was higher than the C_{nose} (geometric mean three times higher). The ratio of ear (C_{ear}) and C_{nose} varied with orientation. At the Back orientation, C_{ear} was lower than C_{nose}, whereas C_{ear} was higher than C_{nose} at the Side and Facing to flow orientations. Velocity affected the ratios of concentrations. At the Back orientation, the chest sampler provided lower overestimates of C_{nose} at higher velocities than at lower values. Mannequin movement, done only at the Back orientation, proved important only for the ear location. Results showed significant and substantial differences between concentrations at the nose and lapel. However, these findings should be interpreted with caution because a very dense tracer gas and an unheated, nonbreathing mannequin were used. In more realistic conditions, the findings probably would show far smaller differences in concentrations at different sampling sites.

Keywords: air sampling, breathing zone, contaminant dispersion, inhalation, sulfur hexafluoride, wake zone

Personal air sampling is a cornerstone of industrial hygiene exposure assessment. When determining personal exposure, it is assumed that the concentration at the "breathing zone" is equivalent to concentration inhaled by a worker. The breathing zone has been defined as encompassing varying distances up to 1 m (3 ft) from the nose and mouth.[1,2] Common practice when assessing personal exposure is to attach the sampler to the collar or to the lapel area of the chest.[1,3,4]

Clearly there must be limits to the validity of sampling at the lapel to represent inhaled air. To take an extreme example, it would seem highly likely that a worker holding a point source inches from his or her nose for close visual inspection would show a higher concentration for a sample taken at the nose than for one taken at the lapel. In the other direction, a worker carrying a small source held against his or her chest would likely show higher concentrations at the lapel than at the nose. However, those extremes are not the only dubious cases. Indeed, one could reasonably question the unproved assertion that the lapel represents the nose for any task involving a source at waist height within reach of the body. For example, lapel concentrations could be much higher than nose concentrations for a worker painting or gluing small objects on a tabletop. Even diffuse sources could produce disparities, such as those in silk screening operations.

There are no conclusive published data that validate the chest as a good location for representing the concentration inhaled. As discussed in following paragraphs, recent contaminant dispersion studies indicate that airflow, and therefore contaminant concentrations, around a worker are not uniform, and thus, sampling location is important.

A large breathing zone that includes locations on the chest is convenient to industrial hygiene sampling, but it is defensible only if concentrations within this area are representative of the concentrations inhaled. However, significant concentration differences have been reported when the sampler is placed in different locations within the supposedly uniform breathing zone.[(5–9)] Recognition that the chest sampler may not be representative of inhaled air is evidenced by development of personal sampling devices designed for locations closer to the nose. For example, Bloor et al.[(10)] developed a personal dust sampler to be attached to a cap bill (at the forehead) and Chien[(11)] proposed a personal sampler suspended from an ear mount and extending to the cheek.

Only limited research has been reported in the literature comparing concentrations at the breathing zone with those at the nose or mouth (hereafter referred to as the nose). Two studies were identified that address the issue. In a field study conducted by Martinelli et al.,[(12)] aerosol concentrations were measured simultaneously at the nose, lapel, and forehead. They found considerable variability in concentrations at different locations, but more often than not, the concentration at the lapel was higher than at the nose and forehead. They speculated that the discrepancies were due to resuspension of dust from clothing, the job performed, and individual work practice differences. Malek[(5)] compared styrene samples taken at the nose, left lapel, right lapel, and chest during boat building. He found that nose concentrations were nearly always lower than samples taken at the other locations.

Compared with field studies, laboratory studies allow better characterization and control over variables that may affect concentration differences with sampling location. Fletcher and Johnson[(13)] found little difference between samples at either lapel and the nose for a subject seated at a table with a neutrally buoyant source on the table. When a denser-than-air source was substituted, they found that concentrations varied with location, with the concentration at the nose the lowest. Although no other published laboratory studies to date have directly addressed the question of how well chest samples estimate the inhalation concentration, studies have been done on contaminant dispersion patterns around a mannequin standing in a cross-draft. Obviously, if dispersion is completely uniform around the mannequin, then all sampler locations should report the same concentration. If dispersion varies about the body, measured concentrations should vary at different sampler locations.

Such mannequin studies[(14–16)] have examined the wake downstream of the body to characterize the wake size and concentrations at various locations within the wake. To allow more tractable mathematical treatment, a human body can be modeled as a group of circular cylinders in a free stream. When a cylinder is observed in a cross-draft, a boundary layer develops around the cylinder and, as friction increases, the boundary layer eventually breaks off, creating turbulent vortices that constitute a wake downstream of the cylinder. This regular, periodic "vortex shedding" occurs only in the range of Reynolds numbers (Re) from about 60 to 5000.[(17)] At lower Re the wake is laminar; at higher Re there is a complete turbulent mixing.

Kim and Flynn[(15)] empirically determined that the dimensionless frequency known as Strouhal number remains constant for velocities of 0.254–1.27 m/sec (50–250 ft/min). From this Kim and Flynn concluded that concentrations should drop with increasing velocity if vortex shedding is the dominant factor in removing contaminant from the wake. Indeed, Kim and Flynn found that over three cross-draft velocities (0.51, 0.76, and 1.27 m/sec) the concentrations at the nose and in front of the chest decreased with increasing velocity. Although relevant for flow into a hood, those velocities are higher than usual cross-draft velocities the authors have observed in industry.

In a smoke visualization study in which vortex size was estimated, Kim and Flynn[(15)] reported that the wake zone profile downstream of a mannequin was not uniform. The wake zone was a much shorter distance downstream at the neck than at the hips. Furthermore, different airflow patterns prevailed in the head region than the chest region. Above the chest, a downwash over the top of the head was dominant, whereas for the chest-to-elbow region a combination of downwash and vortex shedding was important. Above the hip level the net airflow was directed upward, whereas below the hip it was directed downward. Based on the airflow patterns reported by Kim and Flynn, one would expect that concentrations could be different in the head wake zone from those in the torso wake zone if the source were within the torso wake zone during airflow from the back. Indeed, Kim and Flynn[(14)] reported chest concentrations as approximately three times nose concentrations when the source was within the torso wake zone. However, they were not measuring chest concentrations on the mannequin, but rather at seven points on a plane in front of the mannequin.

Whether the sampling location and the source are in the wake zone at the same time is also important because the circulation patterns within the wake transport contaminant throughout its volume. If the source is in the hands and air is flowing from the back, then the face, lapel area, and hands are all within the wake zone. For flow from the side or front, none are in the wake. Thus, one would expect dramatically higher contaminant transport to the face and chest when the flow is from the back, as has been reported in two smoke visualization studies[(15,18)] that used a mannequin holding a source in its hands.

Movement of either the worker or nearby equipment could be expected to affect contaminant dispersion patterns. Ljungqvist[(18)] conducted a smoke visualization study demonstrating that hand movement caused contaminant to disperse more erratically, sometimes traveling up the body toward the face. It is plausible that movement of the torso has greater effects.

Source location is also important. Kulmala et al.[(19)] released a tracer gas at various horizontal and vertical distances from a life-size mannequin in a wind tunnel. They found that tracer gas released above the shear layer of a downwash over the head produced little exposure at the mouth. Likewise, gas released below the hip was caught up in horizontal eddies that transported little contaminant upward into the recirculation zone above the hip level. They also found that exposure concentrations fell sharply with increasing distance of source from the torso, and that concentrations at the chest were generally greater than concentrations at the nose.

Other source factors that may affect contaminant dispersion include contaminant source location(s), the rate of emission, the

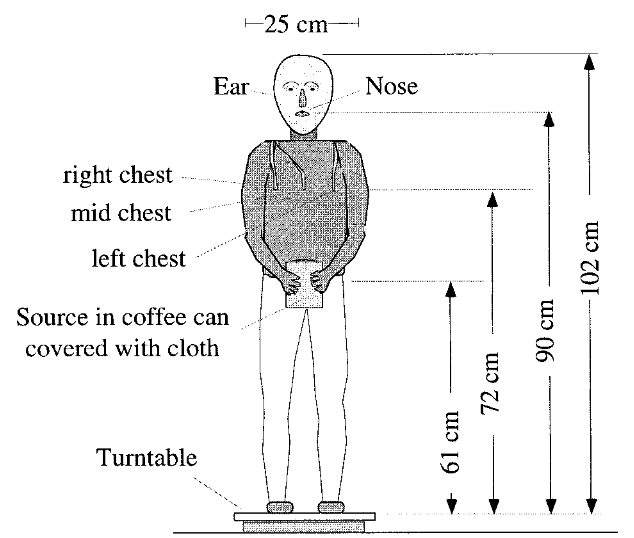

FIGURE 1 Mannequin dimensions and sampler locations

volume and surface area of the source, and whether emission rate is constant or variable.

This study was designed to test whether the chest and ear are good locations for measuring the concentration at the nose. The variables tested were cross-draft velocity, mannequin orientation to the cross-draft, and movement of the mannequin (rotating at different speeds through an 80° arc). The study conditions included use of pure sulfur hexafluoride (SF_6) released from a relatively small source. Pure SF_6 is five times as dense as air. Real sources generally would be almost neutrally buoyant. Hence, one would expect the results for pure SF_6 to exaggerate the vertical concentration gradient. Testing within the relatively uniform flow conditions of a wind tunnel also may produce greater concentration gradients than the turbulent and variable conditions associated with cross-drafts. Thus, this study design simulates what may be a worst case workplace scenario.

METHODS

Mannequin

A flexible, anthropometrically scaled, 1.04 m (41-inch) high mannequin measuring 25 cm (10 inches) across the shoulders was used to simulate a worker (see Figure 1).

The arms of the mannequin were positioned to hold a source of SF_6 as the mannequin stood in a wind tunnel (see Figure 2). The mannequin was positioned at different orientations to the cross-draft, using four cross-draft velocities. Simultaneous 15-min average tracer gas samples were taken at the nose, the ear, and three locations across the chest at lapel level.

The mannequin stood on a turntable (see Figures 1 and 2) midway across the tunnel and 2.13 m (7 ft) downstream from the tunnel entrance. The mannequin was reoriented to cross-drafts from outside the tunnel by manipulating lines attached to the turntable base. For "nonmovement" (i.e., stationary) tests, the mannequin was moved to an orientation with the cross-draft (e.g., Facing, Back, and Side) and remained static during subsequent measurements. For the "movement" portion of the study, the mannequin was moved in an 80° arc by a motor-driven pulley system attached to the base (see Figure 1). Its back was to the cross-draft for all movement conditions. Movement was either 8 or 16 cycles per minute, depending on the selected pulley/belt arrangement.

Wind Tunnel

The wind tunnel dimensions and design are shown in Figure 2. The wind tunnel fan was controlled by adjusting the fan motor

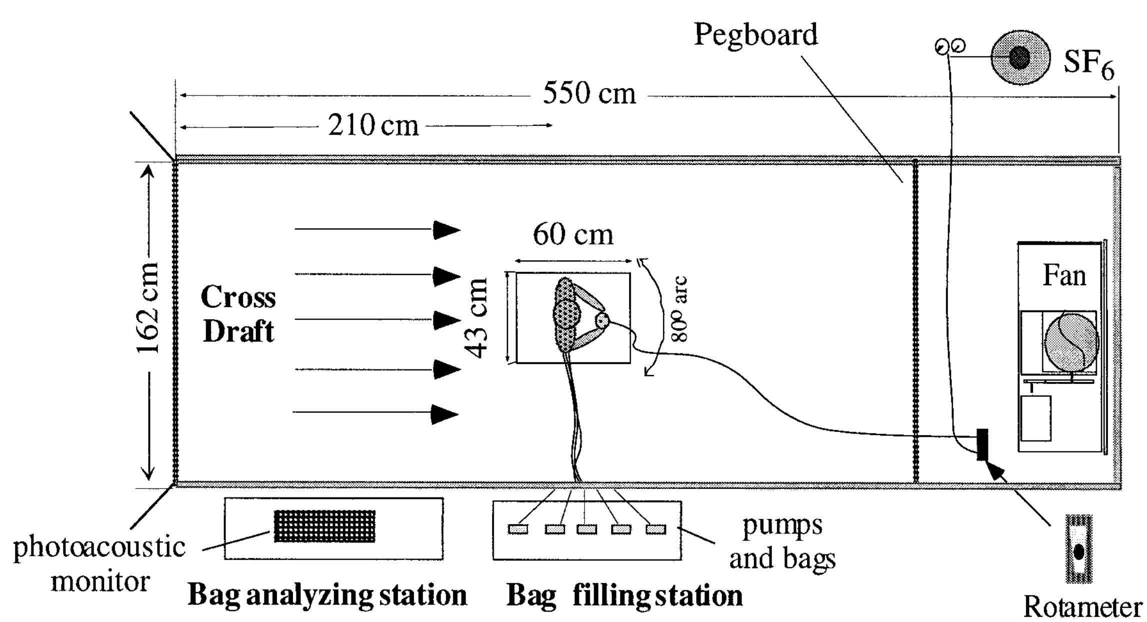

FIGURE 2: Plan view of the wind tunnel

speed with a digital controller. Velocities of 0.05, 0.11, 0.24, and 0.41 m/sec (10, 22, 47, and 80 ft/min) employed in this study represent a broad range. The three lower values represent the range of typical cross-drafts that the authors have measured in industry using a stopwatch, a marked distance, and soap bubbles or a visible smoke. However, it is important to note that cross-draft velocities in industrial settings can change quickly in speed and direction, especially in the winter in buildings with insufficient makeup air. In addition, the velocity profiles on a factory floor are unlikely to be as uniform as those produced in a wind tunnel. The higher velocity is within the lower end of the range used in large ventilation booths and was within the capabilities of the apparatus then on hand.

For the higher wind tunnel velocities, wind tunnel airflows were determined by Pitot traverse of the exhaust duct, and the average wind tunnel velocity was computed by dividing the airflow by the wind tunnel cross-sectional areas. For the lowest wind tunnel velocity, the duct velocity was too low for accurate velocity pressure measurements. Instead, the thermoanemometer was used to traverse the exhaust duct. The calibration of the thermoanemometer was checked at the two higher velocities by comparing centerline velocities taken with the thermoanemometer with values measured using the Pitot tube and pressure sensor at the same conditions.

In preliminary measurements, 20-point traverses of the wind tunnel cross-section at the location of the mannequin found that the wind tunnel velocities varied with grid location with a coefficient of variability of 11%. In addition, the velocities within 2 ft of the mannequin all were within 8% of the average wind tunnel velocity. Hence, the velocity at the mannequin was unlikely to have varied substantially from the value determined from duct traverses.

For the velocities employed, the Reynolds numbers for the flow around the mannequin using the width of the shoulders as the length dimension were 850, 1900, 4000, and 6800, respectively. The shoulder width is a reasonable compromise here because the greatest distance across the arms and back was somewhat larger, but the width of the head and neck were considerably smaller.

Tracer Gas Sampling and Analysis

The flow rate of the tracer gas, undiluted SF_6, was adjusted to 0.1 L/min with a calibrated rotameter/valve assembly. The gas flowed into the bottom of a 10-cm (4-inch) diameter, 11.4-cm (4.5-inch) high metal can with a 5-cm (2-inch) thick foam plug (for even dispersion) to represent a contaminant source. The mannequin held the source at waist height 15 cm (6 inches) out from its body (see Figure 1).

Samplers on the body of the mannequin were one-eighth inch internal diameter polyvinyl chloride tubing. Inlets were located at the nose, in front of the ear at the bottom of the ear lobe, and in three locations 5 cm (2 inches) apart across the chest, and 11.4 cm (4.5 inches) below the shoulder seam (see Figure 1). Three chest locations were chosen to evaluate variability in chest locations because there is no ''standard'' chest location. Sampler tubing ran down the inside of the mannequin's clothing to the floor. Preliminary tests were conducted to assure that there was no absorption or retention of SF_6 in tubing, pumps, or sampling bags.

Simultaneous samples were drawn from each location into 10-L Tedlar® sampling bags, providing a time-weighted average sample for analysis. Air samples were gathered with five Gilian model LFS 113DC low flow sampling pumps located outside the wind tunnel. Samples were pulled simultaneously from tubing through pumps into different sample bags at a rate of 0.2 L/min for 15-min periods. After sampling, the bags were closed and immediately analyzed with a Bruel & Kjaer Model 1302 photo acoustic monitor. The stated lower quantitation limit was 0.005 ppm.

TABLE I. Summary of Ratios of Replications

Conc. at	Abbrev.	Count[A]	Geo. Mean	Geo. Std.
Ear	C_{ear}	15	0.93	1.50
Mean chest[B]	C_{chest}	13	1.01	1.47
Left chest	C_{left}	13	1.00	1.30
Middle chest	C_{middle}	13	1.02	1.59
Right chest	C_{right}	12	0.90	2.04
Nose	C_{nose}	13	1.00	1.62

[A]Cases where concentration $>$ 0.3 ppm.
[B]Geometric mean of C_{left}, C_{middle}, and C_{right}.

Prior to data collection the authors changed the photoacoustic monitor's internal calibration coefficients to match data collected using SF_6 standards prepared from known volumes of compressed air and SF_6. After the completion of data collection, a factory calibration of the photoacoustic monitor revealed that the authors' calibration was faulty due to an error in standards preparation. Fortunately, the original coefficients set at the factory proved to be extremely accurate (less than 2% deviation) when the instrument was checked at the factory. By mathematical manipulation it was possible to transform the readings taken during the experiments to match the readouts that would have occurred with the correct internal coefficients.

Study Design

Test conditions included every combination of three orientations to the cross-draft (Facing, Side to, and Back to the cross-draft) and four velocities: 0.05, 0.11, 0.24, and 0.41 m/sec (10, 22, 47, and 80 ft/min). Once a mannequin orientation was set, test measurements were taken at each velocity after a 45-min equilibration period between velocity conditions to allow residual effects of previous conditions to diminish to insignificant levels. Velocity and source emission rate were checked at the beginning and end of each sampling period.

Data were collected in two phases. First, all orientations and velocity conditions were sampled without movement (i.e., stationary mannequin). On a subsequent day, all stationary conditions were repeated in another round of sampling. For the next phase, concentrations were measured at each of two movement rates at each velocity, but only for the Back orientation. On a subsequent day, the movement sampling was repeated.

Thus, there was a total of two replications for each combination of velocity, orientation, and mannequin movement tested.

RESULTS

Replications

Each study condition was tested twice. Initial tests and replicates were always done on different days. As shown by the geometric standard deviations in Table I, the results were quite variable. The computations of descriptive statistics for Table I excluded cases where both replications were below 0.3 ppm. They were excluded because they were so much lower than other concentrations, and the variability for conditions that produced higher concentrations were of greater interest. Pooled t-tests for differences between first day and second day results

TABLE II. Concentration (ppm) and Concentration Ratios for All Conditions

Orientation and Velocity	Count	Geometric Means and (Geometric Standard Deviations[A])				
		C_{nose}	C_{chest}[B]	C_{ear}	C_{chest}/C_{nose}	C_{ear}/C_{nose}
Back[C]—all vel.	24	15 (8.0)	44.2 (4.7)	11.6 (6.5)	2.9 (2.0)	0.8 (1.6)
0.05 m/sec	6	1.2 (2.4)	4.9 (1.6)	1.0 (1.8)	4.1 (1.6)	0.82 (2.1)
0.11 m/sec	6	4.4 (2.2)	25 (1.3)	4.6 (2)	5.8 (1.9)	1.1 (1.6)
0.24 m/sec	6	73 (1.4)	167 (1.1)	49 (1.2)	2.3 (1.4)	0.67 (1.2)
0.41 m/sec	6	136 (1.2)	184 (1.0)	80 (1.4)	1.4 (1.2)	0.59 (1.3)
Side—all vel.	8	0.08 (7.3)	0.1 (12.0)	0.9 (3.8)	1.5 (3.1)	11.5 (10.8)
0.05 m/sec	2	0.65	3.43	2.3	5.3	3.5
0.11 m/sec	2	0.27	0.20	0.2	0.7	0.7
0.24 m/sec	2	0.02	0.02	0.5	1.0	25.0
0.41 m/sec	2	0.01	0.01	2.6	1.0	260.0
Facing—all vel.	8	0.03 (2.8)	0.2 (7.1)	0.04 (3.3)	6.0 (3.3)	1.5 (1.5)
0.05 m/sec	2	0.04	0.53	0.09	13.3	2.3
0.11 m/sec	2	0.08	1.34	0.13	16.8	1.6
0.24 m/sec	2	0.02	0.06	0.02	3.0	1.0
0.41 m/sec	2	0.01	0.05	0.02	5.0	2.0

[A]All movement speeds.
[B]Geometric mean of three values across the chest.
[C]Shown where more than two values.

showed no significant differences ($p>0.2$) between the two replications for any sampling location at any orientation to the airflow. This was true whether or not very low concentrations were excluded from the analyses.

Results of the nonmovement conditions are presented first because nonmovement measurements were taken at all three positions to flow (Back, Side, and Facing). To simplify the discussion, the geometric mean of the three samples at the chest is employed as the chest value instead of each individual chest sampling concentration.

Chest samples always produced the highest concentrations. Ear samples produced concentrations (C_{ear}) that were sometimes higher and sometimes lower than C_{nose}, depending on velocity and orientation. As shown in Table II and in Figures 3a–c, exposure concentrations were orders of magnitudes higher for the Back flow position than for the Side and Facing orientations (note the difference in scales for Figures 3a, b, and c). A "time-weighted" exposure with equal time spent at all three orientations would be completely dominated by the Back orientation conditions, which would contribute 99.2% of the hypothetical exposure.

At the crucial Back orientation (see Figure 3a), concentrations increased exponentially as velocity increased (i.e., roughly linear in a log-log plot). For the much lower exposures found for the Front orientation (Figure 3b) and Side orientation (Figure 3c), concentrations generally fell as velocity increased, meeting expectations. The exception was values for C_{ear} for the Side orientation, which suggest a minimum concentration at intermediate velocities.

Since there appeared to be some strong linear relationships between Log[concentration] and Log[velocity], the concentrations and velocities both were log-transformed for statistical analyses. For all three sampling locations, analysis of variance (ANOVA) demonstrated that the interaction of velocity and orientation was statistically significant at $p<0.002$ (see Table III) for all three sampling locations. Orientation considered as a main effect was significant ($p<0.001$) for C_{chest} and C_{nose}. Log[velocity] was significant as a main effect only for Log[C_{nose}]. This confirms that the relationship between concentration and velocity was quite different for each orientation.

Exposure Concentrations—Movement Conditions

To fit within time and resource constraints, the movement portion of the study was conducted using only the Back orientation, the orientation associated with vastly higher concentrations in the nonmovement portion of the study described in preceding sections.

Figures 4a–c illustrate the effects of motion on concentrations at the nose, chest, and ear for different movement speeds. The results were consistent with findings for the nonmovement data for Back orientation. As cross-draft velocity increased, concentrations increased at all sampler sites and movement conditions (see Table IV). Values of C_{chest} were higher than C_{nose} values, and C_{ear} values were lower than C_{nose} values for all movement speeds.

As shown in Table V, ANOVA for each dependent variable found that velocity was significant for concentrations at all locations. Movement rate was significant ($p<0.05$) for concentrations measured at the nose and ear. The interaction of velocity and movement rate was significant for concentrations at the ear. It also was significant at the nose ($p=0.024$) if movement rate was treated as a continuous variable, perhaps reflecting a slight increase in statistical power.

Ratios of Concentrations for Movement and Nonmovement Cases

The main goal of this study was to investigate the agreement between lapel, nose, and ear sampling locations. If the ratio between the concentrations at two locations was statistically indistinguishable from a value of unity, then one could not reject the hypothesis that there were no differences. For such statistical analyses, the ratios of C_{chest} to C_{nose} and C_{ear} to C_{nose} were log-transformed. That allowed analyses of the differences in logs of dependent values (e.g., $\log[C_{chest}] - \log[C_{nose}]$), which is mathematically equivalent to the logs of the ratios of the values (e.g., $\log[C_{chest}/C_{nose}]$). Because the nonmovement data included Side and Facing orientations and the movement data did not, movement and nonmovement data were analyzed separately. Note that the movement data included the Back orientation portion of the nonmovement data

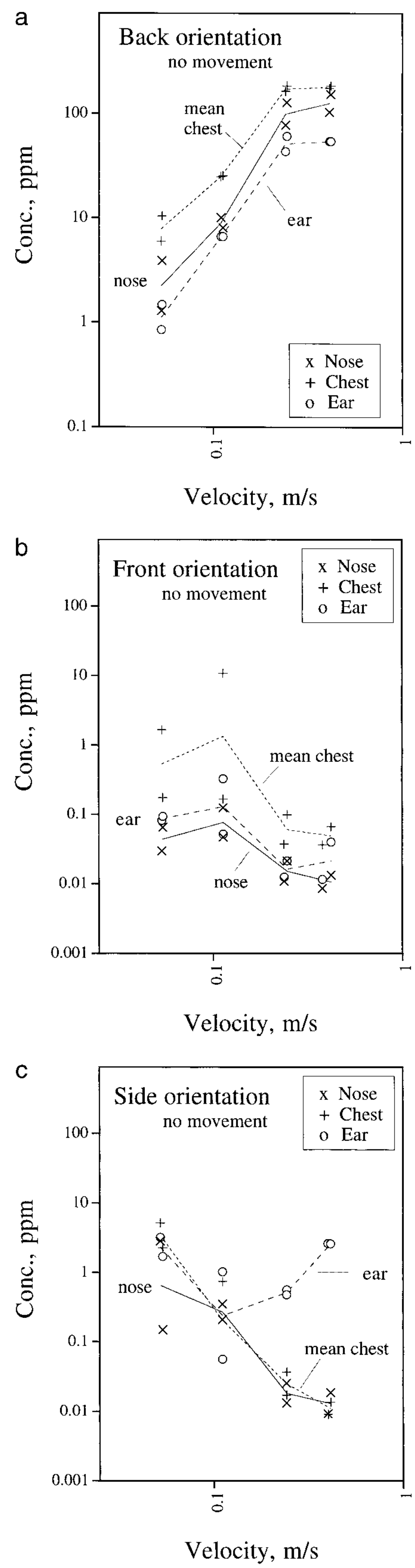

FIGURE 3. (a) Concentrations for Back orientation with no movement; (b) concentrations for Front orientation with no movement; and (c) concentrations for Side orientation with no movement

to allow investigation of movement speed. ANOVA was performed with velocity considered both as a log-transformed continuous variable and with movement considered both as a continuous variable and as a discrete variable.

Comparison of Concentrations across the Chest

The differences among the three samples collected concurrently 5 cm (2 inches) apart across the chest varied with velocity and orientation. For the important Back orientation, the ratio of left lapel to middle (C_{left}/C_{middle}), and right lapel to middle (C_{right}/C_{middle}), appeared to be both more variable and higher for the two lower velocities than for the two higher velocities. ANOVA of the Log(C_{left}/C_{middle}) and Log (C_{right}/C_{middle}) showed movement speed to be unimportant ($p>0.4$) for both ratios. For Log[C_{left}/C_{middle}], velocity was significant ($p<0.05$) whether velocity was log-transformed or not. For Log[C_{right}/C_{middle}], velocity was not significant ($p>0.15$) for the same analyses.

Compared with Back orientation conditions, the ratios for both the Side and Front orientations showed a much wider range of ratios and no clear pattern of change with velocity. Similar analyses showed insignificant differences between C_{left} and C_{right} ($p>0.2$).

The geometric mean of the three chest locations (C_{chest}) was employed for all subsequent analyses because analyses using each chest location individually produced marginally different results.

Comparisons of Concentrations at Nose, Chest, and Ear

As shown in Tables II and IV, the concentrations at the chest (C_{chest}) were much higher than the concurrent concentrations at the nose (C_{nose}). For the very high exposures of the Back orientation, C_{chest} averaged 2.9 times C_{nose}. Concentrations at the ear (C_{ear}) were less than 80% of the corresponding C_{nose} values for the crucial Back orientation, but typically were higher than C_{nose} for the very low exposures at the Side and Facing orientations.

For the Back orientation, values of C_{chest}/C_{nose} declined exponentially with increasing velocities for the nonmovement conditions (see Figure 5a), falling from a geometric mean of 3.2 at 0.05 m/sec to 1.4 at 0.41 m/sec. For the slow and faster movement speeds the ratios display more complex patterns with changing velocity (see Figures 5a and 5b). Values of both ratios were higher with movement of the mannequin than for nonmovement conditions.

For the Front and Side orientations the range of ratios was much greater than the ranges found for the back orientation (note greater ranges in vertical axes of Figures 5c and 5d). C_{chest}/C_{nose} replicate values were erratic at the two lower velocities but were consistent for the lower concentrations found at the two higher velocities. For the Side values, the ratios approached unity. For the Side orientation data, Log[C_{ear}/C_{nose}] was extremely high for the two highest velocities. However, it should be remembered that the concentrations of both C_{ear} and C_{nose} typically were very low in those conditions.

As shown in Tables IV and V, velocity and orientation significantly affected the ratio of C_{chest}/C_{nose} and C_{ear}/C_{nose} for stationary conditions. Unsurprisingly (see Figures 5a and 5b), the interaction of velocity and orientation was not significant ($p>0.20$) for Log[C_{chest}/C_{nose}] and was significant ($p<0.005$) for Log[C_{ear}/C_{nose}]. When the crucial Back orientation was analyzed alone, Log[C_{chest}/C_{nose}] was linearly related to the Log[velocity] ($p<0.005$, adj.Rsq= 0.72). The relationship between Log[C_{ear}/C_{nose}] and Log[velocity] was nearly random ($p>0.45$).

TABLE III. P-Values for ANOVAs for Nonmovement Concentrations

Source	df	Log C_{nose}	Log C_{ear}	Log C_{chest}	Log C_{ear}/C_{nose}	Log C_{chest}/C_{nose}
Log[velocity]	1	0.19	0.17	0.009	0.022	0.03
Orientation	2	≤0.001	0.13	0.007	0.045	0.006
Log[velocity]*orientation	2	≤0.001	0.001	≤0.001	0.003	x[A]

[A]x = p > 0.50 and excluded from model in determining other p-values.

For the movement data (see Table V) and Log[C_{chest}/C_{nose}], the term for Log[velocity] was significant ($p<0.001$). When movement rate was treated as a continuous variable, movement was significant ($p<0.05$). When movement was treated as a discrete variable, it was not quite significant ($p>0.10$) due to the increased degrees of freedom required. For Log[C_{ear}/C_{nose}], movement rate was significant ($p<0.05$) whether treated as continuous or discrete, but Log[velocity] was not significant in either analysis.

Smoke Visualization

When smoke was released near the mannequin (see Figure 6), one could observe a downwash over the mannequin's face for Back orientation similar to that observed by Kim and Flynn.[15] That flow provided additional clean dilution air to the face but not to the torso. In addition, smoke released into the torso wake zone appeared to circulate up from the torso to the face with much less vigor than it circulated in front of the torso.

With airflow from the back, the source was in the combined torso/head wake zone. The sampling inlets for the chest and nose sampling inlets were in the wake, but the sampling inlet for the nose was located in the clean air streaming around the face, so one could reasonably expect concentrations at the ear to be lower than at other sites. The source also was closer to the chest than the nose, so the values of C_{chest} may have been greater than C_{nose} in part because of simple proximity to the source. However, the downwash over the face very clearly reduced visible smoke concentrations above the chin.

For flow from the front, none of the samplers were within the wake zone, which was now behind the body. When released near the source in front of the torso, smoke streamed around the torso with very little moving toward any sampling inlet. Thus, one would expect simple proximity to rule and concentrations to be higher at the chest and concentrations at the nose and ear to be the same.

For flow from the side, the nose and most of the chest were out of the wake zones. Because the air flowed from the left shoulder to the right, the right ear was within the head wake zone and the nose was not. None of the chest inlet locations were within the wake, including the right lapel sampler. Thus, one would expect the ear site to receive the highest concentrations (it did, as shown in Figure 5d) but no site to show high exposures.

DISCUSSION

The concentrations for Side and Facing were trivial compared with values measured for Back flow conditions (see Table III and Figures 3a–c). Moving the mannequin through an 80° arc (Back flow only) modestly reduced concentrations (see Figures 4a–c). The reductions were significant ($p<0.05$) for C_{nose} and C_{ear}, but not for C_{chest} (see Table IV). That may be explained by the observation that the mannequin's motion rotated the nose and ear (but not the chest) out of the wake zone for a portion of the time. Concentrations decreased exponentially with velocity for the nonmoving Side and Front orientations (see Figures 3b and 3c). In nearly all Back orientation cases, as velocity increased, measured concentrations at all five sampler locations increased exponentially (Figures 3 and 4). That appears to disagree with the findings of Kim and Flynn[14] and Kulmala et al.,[19] who found decreasing concentrations at increasing velocities. The findings cannot be compared directly with Kim and Flynn due to the much lower velocities in this study, but the highest two velocities overlap those in Kulmala et al. The measured chest concentrations for both studies were taken at points in a horizontal plane in front of the mannequin rather than on the body of the mannequin, so the C_{chest} results may not be directly comparable.

In agreement with Malek,[5] Kim and Flynn[14] and Kulmala et al.,[19] concentrations near the chest were higher than concentrations at the nose. Values of C_{chest} in this study were almost always (34 of 36 samples) higher than the corresponding C_{nose} values. The geometric mean for chest samples (see Table III) was 2.9 times higher than the C_{nose} samples, but that ratio varied significantly ($p<0.05$) with velocity, orientation, and rate of movement (see Tables III and IV).

Movement tended to increase C_{chest}/C_{nose} and, to a lesser degree, C_{ear}/C_{nose}. C_{chest} values were not significantly affected by movement at the Back orientation, but C_{nose} values were significantly reduced (see Table IV). Thus, as the mannequin's motion rotated the nose out of the head wake zone for a portion of the time, the ratio of C_{chest}/C_{nose} increased substantially (see Figure 5a and Table IV).

The values of C_{ear}/C_{nose} were sometimes greater than unity and sometimes less, depending mostly on orientation. At the important Back orientation, C_{ear} values were lower than C_{nose} if the mannequin was not moving, and were generally (but not always) lower when the mannequin was moving at either rate. For the nonmoving conditions, the value of C_{ear}/C_{nose} varied significantly with velocity and orientation (see Table III). C_{ear} values were nearly always higher than C_{nose} at the Side and Facing to flow orientations. At the Side orientation C_{ear} values were sometimes dramatically higher than C_{nose}. When the effects of movement were investigated at the Back orientation, C_{ear}/C_{nose} varied significantly (see Table IV) with movement rate and nonsignificantly ($p>0.07$) with Log[velocity].

Unlike the concentrations, the ratio of concentrations did not vary exponentially with velocity (i.e., the log of the ratio was not strongly linear with the log of velocity). The appearance of the data for the Back orientation (see Figures 5a and 5b) was of a quadratic relationship between log of the ratios and Log[velocity]. However, the data were too sparse to analyze the significant of quadratic terms. The graphs reveal the possibility of a peak value for the ratios in the middle of the velocity range. For the Front and Side orientations, the ratios did not appear to fall into any specific pattern.

The decline in C_{chest}/C_{nose} for the Back flow condition with

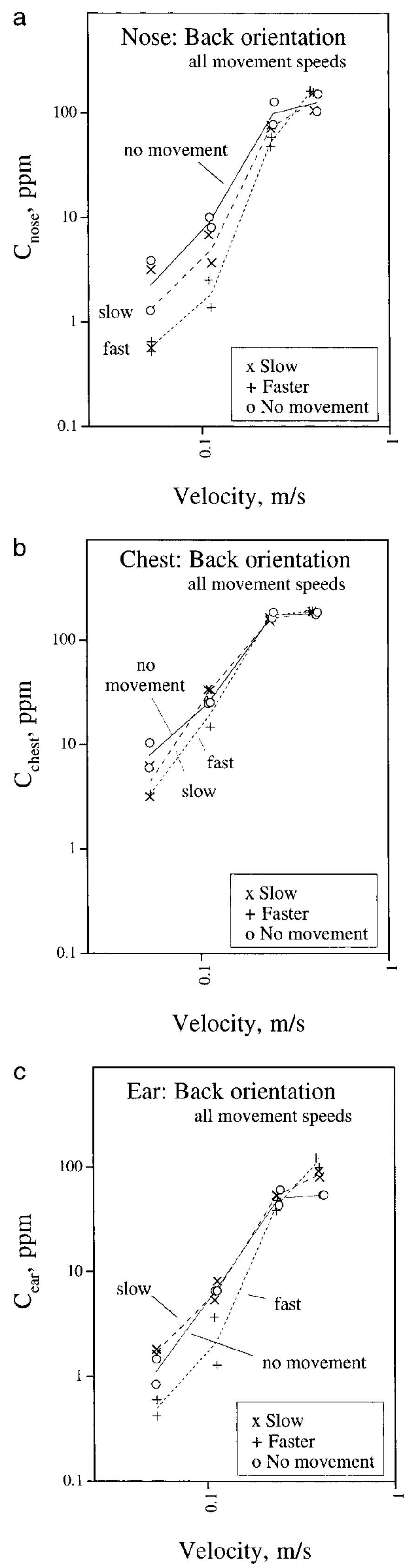

FIGURE 4. (a) Effect of movement on $C_{nose;}$ (b) effect of movement on $C_{chest;}$ (c) effect of movement on C_{ear}

increasing velocities may be explained by the downwash over the head observed with smoke during the study. The downwash would tend to reduce the concentration at the face far more than at the chest. With the greater momentum of the air at higher velocities the downwash could be expected to fall less steeply, thus sweeping the contaminant away from the face less effectively.

The findings from this study may provide a better explanation for the findings of Martinelli et al.,[12] who speculated that their lapel samples were often higher than nose or forehead samples due to dust resuspension from clothing. The discrepancy may actually have been due to the effect of airflow patterns near the workers' bodies.

Effect of Scaling

Because the mannequin height (41 inches) was 60% of an average worker height, a question of scaling to real life dimensions arises. The model system should be dynamically equivalent to a full size system when Re are equal, otherwise differences in turbulence levels can affect results.[20] Re is proportional to size and velocity. If linearly scaled for Re, the model velocities of 0.05–0.41 m/sec (10–80 ft/min) used in this study would be equivalent to velocities of 0.031–0.248 m/sec (6.1–48.8 ft/min) for an average-sized worker.[21] However, linear scaling is appropriate only for laminar flow conditions.[20] Because the values of Re for the mannequin's torso in this study (1000–7200) extended into the intermediate turbulent flow range, the appropriate correction for scaling may be somewhat less than linear with size. Thus, equivalent velocities may be somewhat closer to measured velocities.

The authors found no published studies that tested size effects for flow around mannequins. Because velocity was a significant factor for nearly all conditions tested, the question of appropriate scaling is important and should be the topic of future research.

Mannequin and Source Location

Other common source-sampler relationships were not explored in this study. For example, in an industrial setting, the source frequently is fixed in one place while the worker changes position. In this study the source was held in the mannequin's hands, ensuring that the source was within the wake zone when airflow was from the back. Other source locations would likely produce less severe deviations in concentration with sampling location. If the source were located outside the wake zone, or if the source were dispersed more uniformly, one would expect location effects to diminish. For example, if the source were uniformly dispersed in the vicinity of a worker, one would expect all sampling locations to report the same concentrations.

If the emissions were uniformly mixed, then location differences would be trivial for gas and vapor contaminants, but for effects of air movement on particle size distribution, sampler location may be important for particulates even when the contaminant is initially uniformly dispersed.[22]

Implications for Estimating Exposure

This study suggests that chest samples may not always provide good estimates of inhalation concentrations for situations in which the source is near the worker's wake zone. However, the study design was flawed by use of undiluted SF_6 and its release from a relatively small source at a relatively high rate. In addition, the applicability to humans from results taken with mannequins

TABLE IV. Concentration (ppm) and Concentration Ratios for Movement Conditions

Movement and Velocity	Count	Geometric Means and (Geometric Standard Deviations[A])				
		C_{nose}	C_{chest}[B]	C_{ear}	C_{chest}/C_{nose}	C_{ear}/C_{nose}
All movements						
0.05 m/sec	6	1.2 (2.4)	4.9 (1.6)	1.0 (1.8)	4.1 (1.6)	0.82 (2.1)
0.11 m/sec	6	4.4 (2.1)	25 (1.3)	4.6 (2.0)	5.8 (1.9)	1.1 (1.6)
0.24 m/sec	6	73 (1.4)	167 (1.1)	49 (1.2)	2.3 (1.4)	0.67 (1.2)
0.41 m/sec	6	136 (1.2)	184 (1.0)	80 (1.4)	1.3 (1.2)	0.59 (1.3)
No movement						
0.05 m/sec	2	2.2	7.9	1.1	3.5	0.50
0.11 m/sec	2	9.0	25	6.6	2.8	0.74
0.24 m/sec	2	99	172	51	1.7	0.52
0.41 m/sec	2	125	178	54	1.4	0.43
Slow						
0.05 m/sec	2	1.3	4.4	1.7	3.3	1.3
0.11 m/sec	2	5.0	33	6.7	6.7	1.3
0.24 m/sec	2	74	158	54	2.1	0.73
0.41 m/sec	2	127	185	86	1.5	0.67
Fast						
0.05 m/sec	2	0.59	3.4	0.50	5.7	0.85
0.11 m/sec	2	1.9	20	2.2	11	1.2
0.24 m/sec	2	53	171	43	3.2	0.81
0.41 m/sec	2	159	188	110	1.2	0.69

[A]Shown where more than two values.
[B]Geometric mean of three values across the chest.

should be treated with skepticism, particularly if the mannequin neither breathes nor is heated to match human surface temperatures. Finally, in the authors' experience, cross-drafts in workplaces can change quickly in speed and direction. Although this study tried to approach the latter problem using movement of the mannequin torso, it is clearly not the same. Airflows outside a spraybooth may commonly include swirls and other effects of upstream conditions.

Each of these modeling deficiencies could have biased the findings, probably tending to exaggerate the differences between sample concentrations at the nose and lapel. In particular, it is not difficult to imagine that a much less dense mixture rising much more slowly from the source would lead to much lower differences at different sampling locations above the point of release. It is possible that the very high concentration gradients found in this study would be found only in a narrow range of workplace conditions.

However, Malek's[5] findings in real industrial settings using humans doing their normal tasks suggest that there are significant differences between concentrations at the lapel and nose. If supported by additional research, the implications for industrial hygiene would be important. If it is true that the ratio of lapel concentrations to C_{nose} vary substantially with cross-draft velocity, then use of lapel sampling would provide different degrees of protection for different work conditions, leading to misallocation of resources to reduce "high" chest exposures when the inhalation concentrations are relatively low. Furthermore, dose-response studies that employ chest sampling would misclassify rank orders of worker exposure levels, reducing the power of the studies to associate increasing doses with increasing responses. For example, studies comparing lapel samples with biological indices of exposure may underestimate the true correlation between inhalation concentration and the biological response or burden. Interestingly, if exposures are overestimated in such studies, the assumed "safe" inhalation level would be corresponding inflated.

If it also is proven that relative concentrations at the nose, chest, and ear vary substantially with cross-draft velocity and orientation, then no single "correction" factor could allow one to

TABLE V. P-Values from ANOVA for Movement Conditions

Source	df	Log C_{nose}	Log C_{ear}	Log C_{chest}	$\text{Log}\left(\frac{C_{ear}}{C_{nose}}\right)^A$	$\text{Log}\left(\frac{C_{chest}}{C_{nose}}\right)^A$
P-Values with Movement as Discrete Variable						
Log[velocity]	1	<0.001	<0.001	<0.001	0.076	<0.001
Movement	2	0.034	0.006	0.19	0.026	0.11
Log[velocity]*movement	2	0.089	0.013	0.24	x	x
P-Values with Movement as Continuous Variable						
Log[velocity]	1	<0.001	<0.001	<0.001	0.091	<0.001
Movement	1	0.008	0.010	0.056	0.042	0.033
Log[velocity]*movement	1	0.024	0.015	0.079	x	x

[A]x = p > 0.3 and excluded from model in determining other p-values.

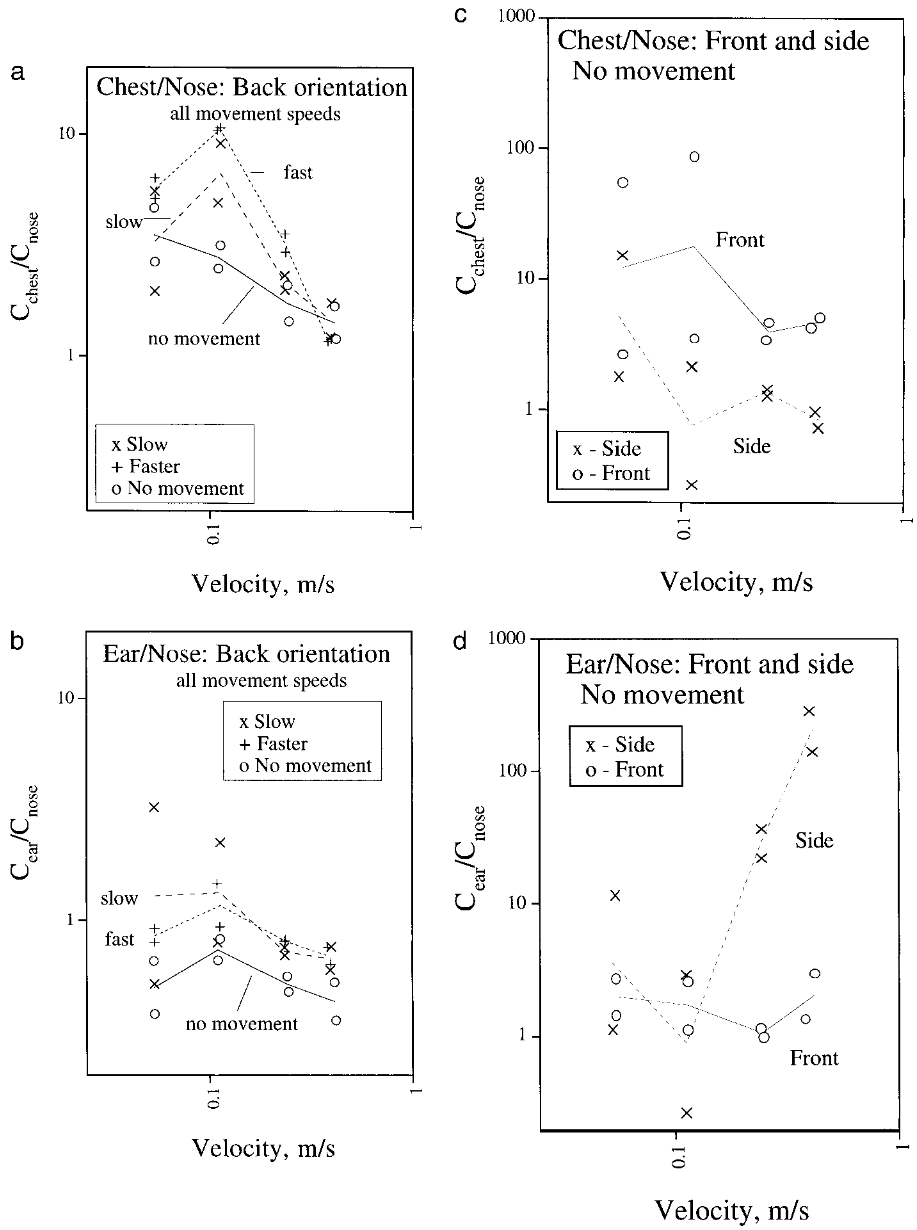

FIGURE 5. (a) C_{chest}/C_{nose} ratios for Back orientation; (b) C_{ear}/C_{nose} ratios for Back orientation; (c) C_{chest}/C_{nose} for Front & Side orientations; (d) C_{ear}/C_{nose} for Front & Side orientations

estimate concentrations at the nose accurately using lapel sampling results. Even if an accurate model were developed that accounted for all environmental factors, it may be impractical to apply because cross-draft velocity, worker orientation, movement, and source dispersion may often vary greatly with both time and location within a given work area. Developing correction factors for each work task and condition (as suggested by Malek[5]) may be feasible with enough sampling data, but it is quite possible that the correction factor could apply poorly to other workers doing the same tasks. Furthermore, the appropriate correction factor could change substantially with seemingly minor changes in work layout, work practices, and airflow patterns.

Finally, if one ignored the caveats on this study and believed that lapel samples always substantially overestimated inhaled concentrations, one might discount a "marginally excessive" lapel sample when the lapel sample was, in fact, a good estimate of the inhaled concentration because of the uniformity of the source or for other reasons.

CONCLUSIONS

For the range of velocities and orientation studied, it was found that for a 60%-height mannequin holding a source in its hands at waist height:

- Concentrations at all sample locations were profoundly higher for the back to the flow orientation than for the side and facing orientations.
- For the crucial backflow orientation, concentrations increased with increasing cross-draft velocities over the range of velocities tested.

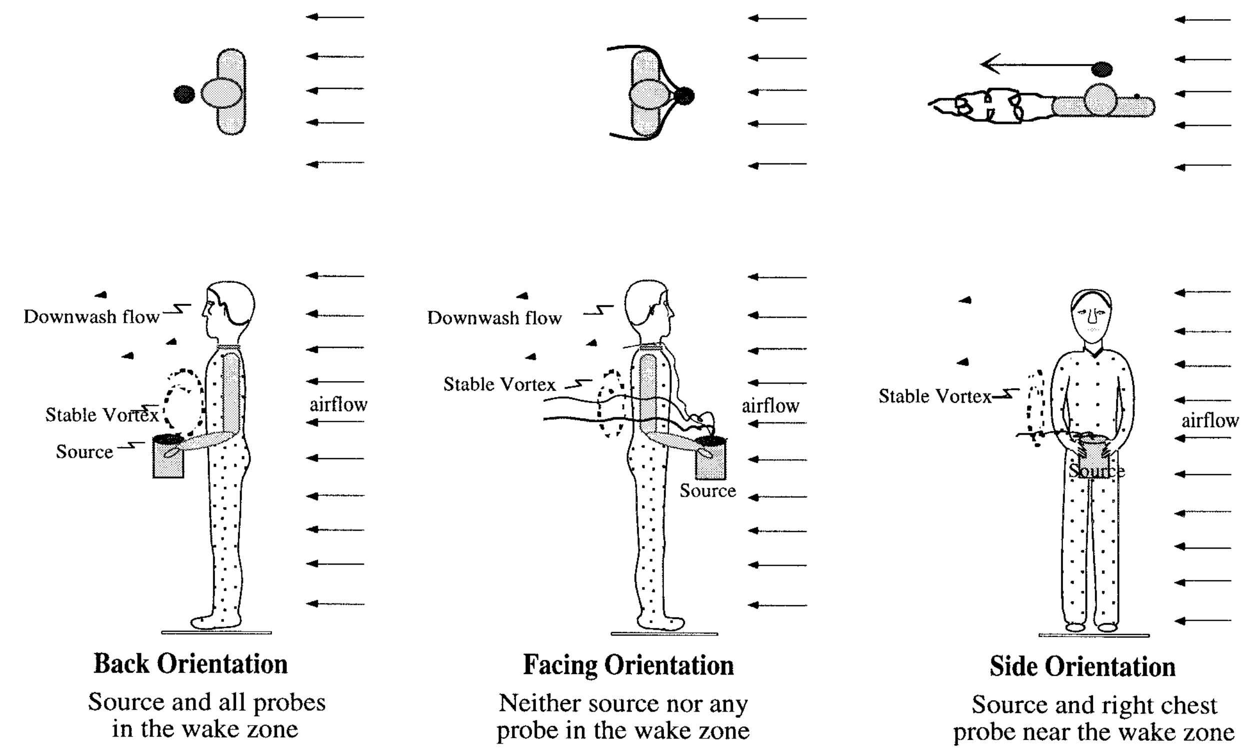

FIGURE 6. Airflow patterns for each orientation

■ The concentrations at the chest averaged about 2.9 times the concentrations at the nose, with the ratio decreasing significantly with increasing velocities. Movement increased the ratios.

■ The ratio of chest to nose concentration varied far too much to allow accurate use of a single ratio to represent all orientations and cross-draft velocities.

■ The concentrations at the ear were sometimes higher and sometimes lower than the concentration at the nose, making the ear a poor choice as a sampling location.

These findings are limited by the use of a mannequin that did not breathe or radiate heat and did not change its posture or the relative positions of its head, arms, or legs. It wore one set of clothing and one hair length, and it did not wear glasses, goggles, or a respirator. In short, it did not represent the vast diversity of workers at work. The implications of the findings also are limited by the single relative location of the contaminant source and the fact that only one tracer gas density (much heavier than air) was employed. On the other hand, there is no convincing body of published evidence supporting the assumption that lapel samples always (or usually) predict inhalation concentrations with substantial accuracy.

Because air sampling results are a fundamental aspect of industrial hygiene practice, further study of this topic is important. Factors that deserve particular attention include the effects of a broad range of velocities, realistic worker motion, and the location and type of source relative to the worker, as well as source dispersion. In addition, the effects of posture, arm and hand location, and obstructions to flow over the head (e.g., hair, caps, and respirators) may be important. Future studies also should consider other sampling locations (e.g., at the base of the neck) and possible designs of unobtrusive apparatus intended to sample near the mouth.

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