Development of Direct Measurement Device for Alveolar Breath Carbon Monoxide

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Abstract

A novel portable device for the direct measurement of alveolar breath carbon monoxide (CO) was developed. The major components of the device include a mouthpiece, non-rebreathing two-way valve, Teflon tube, and CO dosimeter. An alveolar CO measurement can be completed within 1.5 min when using the proposed device and measurement protocol. Measurements could be read to the nearest 0.1 ppm. Humidity did not influence the CO measurements taken by the CO dosimeter, plus there were no problems associated with the recovery and carryover of CO through the device. The criterion for significance in statistical analyses was $p < 0.05$. The average recovery was 103 and 99% for recovery and carryover experiments, respectively. Test results using the proposed alveolar CO measurement system reflected a good reproducibility. This reproducibility was also supported by the finding that the relative standard deviations (RSDs) of the data sets were less than 7% for the loss experiment and less than 8% for the carryover experiment. Consequently, it would appear that the proposed device can be effectively applied to measure CO levels found in breath, thereby overcoming several disadvantages associated with the conventional bag and adsorbent tube sampling methods.

1. INTRODUCTION

Personal exposure to carbon monoxide (CO) exposure is a major public concern because of the toxicity (USEPA, 1991) and urban air prevalence of CO (Apte et al., 1999). CO is a noxious pollutant that binds hemoglobin and inhibits the uptake of oxygen. When an individual is exposed to moderate amounts of CO, he or she can suffer from headaches, nausea, and an incor-

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rect judgment of time intervals. In addition, exposure to CO also increases the risk of coronary artery disease (Apte et al., 1999).

Consequently, accurate dose measurements are important in evaluating adverse health effects, because personal exposure does not always exhibit a linear relationship with the dose level (Lambert et al., 1988). A CO dose can be assessed based on carboxyhemoglobin (COHb) levels since inspired CO is rapidly transferred to the blood and most CO in the body is present in the form of COHb. However, even though COHb is a biological indicator for the amount of CO in the body, the measurement techniques involved are not always feasi-

ble due to the invasive and tedious nature of collecting blood samples. As such, the use of a breath measurement technique in estimating a CO dose can overcome such disadvantages (Lambert *et al.*, 1988; Wallace *et al.*, 1988; Akland *et al.*, 1985; Wallace *et al.*, 1984; Verhoeff *et al.*, 1983). While some health investigators agree that there would be limitations to the accuracy and precision of estimates, the non-invasive and cost-effective nature of breath measurement techniques has encouraged their use in studies of community and occupational exposure to CO.

Several studies have already employed breath measurement techniques for the evaluation of both non-occupational environmental CO exposure and occupational CO exposure. For example, Wallace *et al.* (1984) reported that the mean breath CO concentrations in Denver and Washington D.C. were 7.2 and 5.1 ppm, respectively, while Lambert *et al.* (1988) reported that the mean breath CO concentrations in California were 5.3 and 24.1 ppm for nonsmokers and smokers, respectively. Furthermore, Wallace (1983) reported that smoking and nonsmoking office workers had alveolar CO levels of 8 and 23 ppm, respectively.

Several previous studies (Lambert *et al.*, 1988; Wallace *et al.*, 1988; Cox and Whichelow, 1985; Wallace, 1983; Jabara *et al.*, 1980; Smith, 1977) utilized a bag sampling method for collecting alveolar CO, then the CO content in the breath samples was analyzed using a calibrated CO dosimeter. However, the field transport and use of bags is laborious. Another disadvantage associated with bags is that after each use they must be evacuated and cleaned with clean air prior to being used again. To overcome these disadvantages, a more recent study Lee and Yanagisawa (1995) introduced a simple sampler for measuring alveolar CO. This alveolar CO sampler consists of a mouthpiece, alveolar air trap system using two one-way valves, and adsorbent tube, without any air sampling bags. However, this sampler also has a serious disadvantage in that the adsorbent tubes used for the alveolar CO sampling must be transported to the laboratory for subsequent gas chromatograph analyses. Accordingly, the present study

proposes a device for the direct measurement of alveolar breath CO that can overcome all the above disadvantages, without the use of any air sampling bags.

As such, an alveolar breath sampling device designed by Raymer *et al.* (1990a, b) for the measurement of expired volatile organic compounds (VOCs) was modified to create a new device for alveolar CO measurement. Based on a CO_2 measurement, the alveolar VOC sampler can sample more than 97% of alveolar air, regardless of the breathing rate (Raymer *et al.*, 1990a, b). The main modification is that, whereas the alveolar VOC sampler uses an evacuated canister to collect the alveolar VOC samples, the proposed device replaces the canister with a calibrated CO dosimeter. The alveolar CO measurements obtained using the new device were evaluated relative to the effect of humidity, the CO recovery and memory of the device, and in comparison with the bag sampling method

2. EXPERIMENTAL METHODS

2. 1 Configuration and operation of alveolar CO measurement device

A diagram of the proposed device for the direct measurement of alveolar breath CO is presented in Fig. 1. The major components of the device include a mouthpiece, non-rebreathing two-way valve (Laerdal Medical Co.), Teflon tube (1.3 cm i.d. × 760 cm), and CO dosimeter equipped with a data logging system (CMCD -10P, GASTEC Co.). The tube dimensions were chosen to minimize any mixing of the alveolar air with deadspace air and yet provide a sufficient volume (0.9 L) to contain the alveolar breath (Raymer *et al.*, 1990a).

In operation, the person providing the breath sample inhales ambient room air through the non-rebreathing two-way valve into the Teflon tube. This breath is then withdrawn into the portable calibrated CO dosimeter for monitoring. The inspired ambient room air is recommended to contain as little CO as possible to minimize its possible influence on the expired air concentration. It is further noted that, for the proper use of the
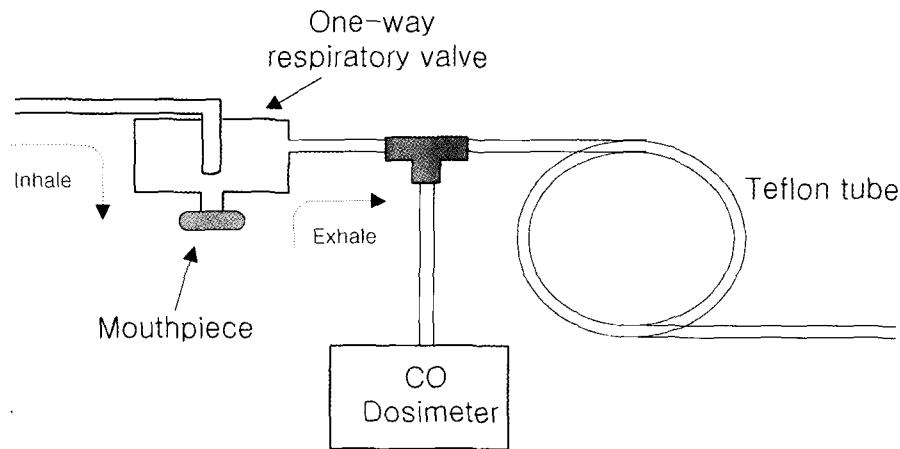
Fig. 1. New device for CO measurement in alveolar breath.

breath CO measurement system, the CO concentration of the inspired ambient room air should be lower than that of the expired air of the subject. By definition, the breath drawn back from the tube is predominantly alveolar in origin, because the majority of the sampled breath is from the end of the expiration. The next exhalation then replenishes the tube with breath before all the air from the previous exhalation is withdrawn. Since the nominal withdrawing flow rate through a CO monitor is 265 ml/minute, the alveolar volume has to be below 133 ml for over-sampling to occur. Such a small alveolar volume is unlikely for deep breathing in a healthy person (Raymer et al., 1990b; Guyton, 1977). When performing the breath measurement maneuver, the duration of the breath-holding and breath-blowing is timed using a clock. By replacing the mouthpiece, the alveolar CO measurement device can be used repeatedly.

The CO dosimeter employs controlled potential electrolysis method to measure CO concentrations. The CO instrumental measurement concentration of the dosimeter ranges from 0.1 to 50 ppm, with a sensitivity of 0.1 ppm. In the current study, the CO monitor was calibrated by checking the zero and span before each use and at specific intervals during the analysis runs. The monitor was equipped with an activated charcoal-Purafil prefilter to remove any potentially interfering

compounds existing in the breath (Lambert et al., 1988; Wallace et al., 1988; Hartwell et al., 1984). The concentration of the span gas employed to calibrate the CO dosimeter was 25 ppm, which was recommended by the manufacturing company of the CO dosimeter. The CO dosimeter also included an auto-zeroing function. For the auto-zeroing function, zero gas was generated by passing ambient air through a CO removal filter. Plus to insure accuracy, the machine was also cross-checked for ambient air CO levels with a nondispersive infrared (NDIR) CO monitor (Model 300, API Inc.) operated by the Taegu Provincial Environmental Management Department (TPEMD). The calibration procedure was performed using monitors powered by fully charged batteries instead of a primary electrical outlet, to prevent differences in the monitor performance when operated by a source of power not used in some fields. Measurements were read to the nearest 0.1 ppm.

In the alveolar CO measurement procedure, the subject was asked to inspire ambient room air for 5 seconds deeply through a new mouthpiece into a non-rebreathing two-way valve, hold the breath for 20 seconds, and then completely blow out for 5 seconds into a temporary storage Teflon tube. Holding the breath for 20 seconds after inspiring a full lung capacity was found to allow enough time for an equilibrium of CO to be established in the arterial blood and alveolar air

(Jones et al., 1958). The exhaled breath was then with-drawn into the portable calibrated CO dosimeter for monitoring. Three consecutive breaths were taken during 1.5 minutes (each breath for 30 s) and the monitoring started right after the first breath and continued for 1 minute. This breathing pattern was determined based on the minimum reading time of the CO dosimeter (1 min) and the principle of breath sampling (Raymer et al., 1990a).

2. 2 Effect of humidity

The effect of humidity on the CO measurements taken by the CO dosimeter was examined by comparing the concentrations of CO standard gases in dry test air with those in humidified test air. The humidity test was performed under two different experimental conditions. For the first experiment, the humidified test air was prepared by a procedure where distilled water was injected into a 1-L Tedlar bag (Lee and Yanagisawa, 1995), then the bag was filled with CO standard gas (100 ppm) and clean dry air to provide a concentration of 1 or 40 ppm. Next, the Tedlar bag was placed in an incubator for four hours at 37°C, then the CO concentration in the bag air was determined using a CO dosimeter. Meanwhile, the dry test air was prepared by just filling the bag with clean dry air and CO standard gas to provide a concentration of 1 or 40 ppm. The same CO dosimeter (dosimeter A) was employed to measure the dry test air and humidified air CO concentrations

four hours after preparation. Ten paired samples of dry test air and humidified air were prepared and measured for each of the two specified CO concentrations. However, this procedure only provided a maximum relative humidity of about 60% for the humidified test air.

Accordingly, to simulate real breath with respect to humidity, another method was developed to prepare humidified air with a relative humidity of near 100%. As such, the humidified test air was prepared by passing dry air (1 or 40 ppm CO) through a humidity generation system in which the distilled water was heated and bubbled to generate water vapor. Meanwhile, the dry test air by-passed the humidity generation system. The CO concentrations in the dry and humidified air, plus the relative humidity were recorded every minute for 10 minutes after a warm-up of 30 minutes. The dry test air and humidified air CO concentrations were measured using two separate CO monitors (Dosimeters A and B), which were the same model, purchased on the same day, and calibrated in the same way.

2. 3 Recovery and carryover of CO through device

The adsorptive and any other possible losses of CO at a low level, plus the memory of CO at a high level were all studied in the laboratory. The system loss was determined by comparing synthetic breath CO concentrations at the inlet and measuring port of the spirometer while a stream of synthetic breath containing CO of
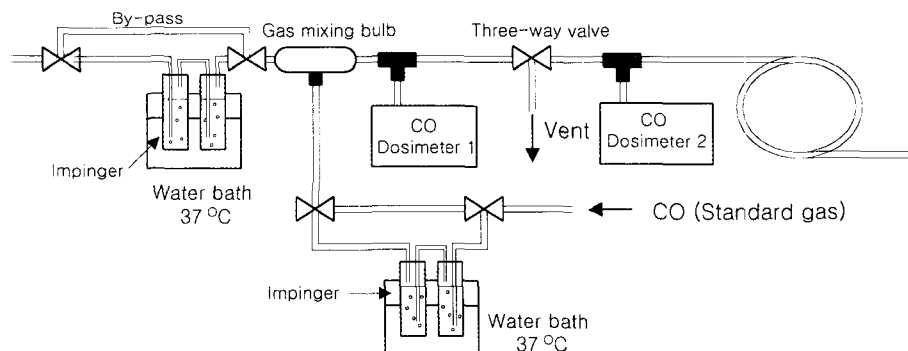

Fig. 2. Schematic diagram of synthetic breath generation system and spirometer.

1 ppm was flowing through the alveolar CO measurement device (Fig. 2). It should be noted that the synthetic breath was only simulated with respect to humidity and not CO_2 and O_2. The CO concentrations at the inlet and measuring port were measured using two separate CO monitors that were the same model. The synthetic breath was generated by passing clean air through a humidity generation system in which distilled water was heated and bubbled to generate water vapor. The humidified air was then mixed with CO to provide a low (1 ppm) concentration level at a flow rate of 6.0 standard liters per minute (SLPM) and introduced into the spirometer. The synthetic breath was passed through the valve by shunting it away from the spirometer before beginning the experiment. As a result, the synthetic stream was established without "conditioning" the internal surfaces of the spirometer. After 10 minutes (assuming an equilibration in the stream), the valve was reversed so that the stream flowed into the spirometer, then five seconds later the CO measurement was started using the second CO dosimeter and the valves were reversed to shunt the flow again. Twenty-five seconds later the flow was switched to the spirometer again for five seconds. Thereafter, the valves were reversed to shunt the flow for 25 seconds and the CO measurement was continued for 60 seconds. This switching was designed to mimic an actual breath measurement pattern. The CO concentration readings using the two CO monitors were performed concurrently. The whole procedure was repeated ten times with a time interval of at least one hour. The testing system was flushed with clean dry air during each interval time period. The whole procedure was repeated another ten times while exchanging the position of the two CO monitors at the inlet and measuring port of the spirometer to minimize any confounding factor resulting from a difference between the two CO monitors.

Another area of interest was how well the spirometer would perform when used to measure a low concentration of CO shortly after measuring a high concentration of CO. Any possible carryover of CO in the device was examined by generating and measuring

synthetic breath containing a high concentration (40 ppm) of CO as per the procedure employed for the recovery test. After the high-level measurement, the CO input concentration was reduced to 1 ppm and measured in the same manner as for the high level. As with the recovery experiment, the whole procedure was repeated ten times with a time interval of at least one hour. In this experiment, the CO measurements were performed concurrently by CO dosimeters located at the inlet and measuring port of the spirometer. The whole procedure was also repeated another ten times while exchanging the position of the two CO monitors at the inlet and measuring port of the spirometer.

2. 4 Comparison with bag sampling-CO dosimeter measurement method

The direct measurement method was compared with bag sampling followed by the CO dosimeter measurement method for the alveolar breath CO levels of 10 nonsmoking subjects. Each subject provided a breath sample for the direct measurement device and a consecutive breath sample for the bag sampling. In the bag sampling procedure, the subject was asked to inspire low CO-level room air deeply for 5 s through a new mouthpiece into a non-rebreathing two-way valve, hold the breath for 20 s, and then blow out for 5 s into a one-liter capacity Teflon bag. This procedure was continued until about 70% of the bag capacity was filled. This breath pattern was consistent with that used for the direct measurement method. The alveolar breath CO content in the sampling bag was analyzed using the same calibrated CO dosimeter as used for the direct measurement method. Informed consent was obtained from each subject who participated in this and the subsequent experiments.

2. 5 Statistical analyses

Statistical analyses were performed using the SAS program (Version 6.1) on a personal computer. Paired sample means were analyzed using paired-samples t-tests. Comparisons of the levels of more than two data sets employed a *Post hoc* analysis (Duncan's multiple-

range test). The criterion for significance in the procedures was $p < 0.05$.

3. RESULTS

3. 1 Cross-calibration of CO dosimeters

To insure accuracy, two CO dosimeters were cross-checked for ambient air CO levels using an NDIR CO monitor operated by the TPEMD. After the dosimeters and NDIR were calibrated against a span gas, the two devices were run at the same place and time to measure and compare ambient CO concentrations. Readings were taken every minute for 5 minutes. Table 1 shows the CO concentrations measured by the machines. The mean and standard deviation values were 0.98 ± 0.08, 0.96 ± 0.11, and 0.94 ± 0.05 ppm for dosimeter A, dosimeter B, and the NDIR monitor, respectively. There were no significant differences in the CO levels among the three machines. This indicates that the dosimeters employed in the current study were comparable with a NDIR monitor for measuring CO concentrations under the given measurement conditions.

3. 2 Humidity effect

The humidity test was undertaken using two different experimental methods. In the first method, the clean dry test air and humidified test air were both prepared in Tedlar bags. In the second, the humidified test air was prepared by passing dry air through a humidity generation system (HGS), whereas the HGS was by-passed for the clean dry test air. The CO concentrations in the clean dry test air and humidified test air measured under each experimental condition are shown in Table 2. The CO concentrations in the clean dry test air and humidified test air prepared in Tedlar bags were not

Table 1. Ambient air CO concentrations (ppm) measured using two CO dosimeters and NDIR monitor.

	Dosimeter A	Dosimeter B	NDIR monitor
Number			
1	1.1	1.0	0.9
2	1.0	0.9	1.0
3	1.0	0.8	1.0
4	0.9	1.0	0.9
5	0.9	1.1	0.9
Mean	0.9_8	0.9_6	0.9_4
S.D.	0.0_8	0.1_1	0.0_5

Table 2. CO concentrations (ppm) in clean dry test air and humidified test air prepared in Tedlar bags and using humidity generation system (HGS).

	Tedlar bag				HGS			
	Low level		High level		Low level		High level	
	Dry air	Hum. air	Dry air	Hum. air	Dry air	Hum. air	Dry air	Hum. air
Number								
1	1.3	1.2(62)	42.1	42.9(59)	1.1	1.0(97)	41.2	40.5(96)
2	1.2	1.2(58)	41.7	42.4(61)	1.2	1.1(96)	40.7	41.5(95)
3	1.1	1.3(59)	40.5	42.8(61)	1.2	1.1(94)	41.3	41.1(98)
4	1.2	1.1(58)	41.1	41.5(61)	1.1	1.2(97)	40.8	41.3(97)
5	1.0	1.2(60)	41.5	40.4(61)	1.2	1.1(95)	41.2	40.7(96)
6	1.1	1.2(63)	40.4	41.3(61)	1.1	1.0(98)	40.9	41.2(95)
7	1.3	1.0(59)	41.9	41.8(61)	1.0	1.1(96)	40.3	40.5(94)
8	1.1	1.2(61)	40.3	42.1(61)	1.2	1.1(93)	40.9	41.3(97)
9	1.2	1.3(60)	41.1	40.6(61)	1.2	1.2(95)	41.5	41.0(96)
10	1.2	1.1(62)	40.9	41.4(61)	1.1	1.1(93)	40.6	41.1(98)
Mean	1.1_7	$1.1_8(60.2)$	41.2	41.7(60.8)	1.1_4	$1.1_0(95.4)$	40.9	41.0(96.2)
S.D.	0.0_9	$0.0_9(1.8)$	0.6	0.8(1.3)	0.0_7	$0.0_7(1.7)$	0.4	0.3(1.3)
%RSD	8	8	1	2	6	6	<1	<1

Note. Low and high levels are the concentrations prepared to provide 1 and 40 ppm, respectively. The values in parenthesis are the relative humidity of the humidified air (%).

significantly different from each other for the two CO levels tested. For the low standard gas level (1 ppm), the mean and standard deviation values were 1.17 ± 0.09 and 1.18 ± 0.09 ppm for the clean dry test air and humidified test air, respectively. The mean and standard deviation relative humidity values for the humidified test air were $60.2\pm1.8\%$. For the high standard gas level (40 ppm), the mean and standard deviation values were 41.2 ± 0.6 and 41.7 ± 0.8 ppm for the clean dry test air and humidified test air, respectively. The mean and standard deviation relative humidity values for the humidified test air were $60.8\pm1.3\%$. However, since the relative humidity of real breath is close to 100%, the humidified air with about 60% relative humidity does not represent real breath with respect to humidity. Nonetheless, the test with about 60% relative humidity still indicates that humidity did not effect the CO measurement taken by the CO dosimeter.

Similar to the Tedlar bag method, the HGS method showed that the CO concentrations in the clean dry test air and humidified test air were not significantly different from each other for the two CO levels tested. For the low standard gas level (1 ppm), the mean and standard deviation values were 1.14 ± 0.07 and 1.10 ± 0.07 ppm for the clean dry test air and humidified test air, respectively. The mean and standard deviation relative humidity values for the humidified test air were $95.4\pm1.7\%$. For the high standard gas level (40 ppm), the mean and standard deviation values were 40.9 ± 0.4 and 41.0 ± 0.3 ppm for the clean dry test air and humidified test air, respectively. The mean and standard deviation relative humidity values for the humidified test air were $96.2\pm1.3\%$. As such, the data from both of the above methods confirmed the good reproducibility of the experimental systems. This was further supported by the finding that the relative standard deviations (RSDs) of the data sets were less than 8% for the bag method, and less than 6% for the HGS method.

3. 3 Recovery and carryover of CO through device

The results of the experiment testing for any CO loss

Table 3. Percent recovery of CO related to system loss and carryover experiments for two experimental runs for each experimental condition.

	Loss experiment[a]		Carryover experiment			
			Low level		High level	
Number	Run 1	Run 2	Run 1	Run 2	Run 1	Run 2
1	100	92	91	100	96	101
2	109	100	109	90	103	94
3	100	111	100	100	104	106
4	109	110	108	91	102	103
5	111	100	109	89	105	99
6	100	100	90	108	104	98
7	93	108	100	100	102	97
8	110	100	108	92	107	99
9	100	93	91	100	99	99
10	109	108	110	92	94	102
Mean	104	102	102	96	102	100
S.D.	6	7	8	6	4	3
%RSD	6	7	8	6	4	3
Avg	103		99		101	

Note. Low and high levels are the concentrations prepared to provide 1 and 40 ppm, respectively. For the two runs (Run 1 and Run 2), the position of the two CO monitors was exchanged at the inlet and measuring port of the spirometer. The percent recovery was calculated by dividing the measuring port CO concentration by the inlet CO concentration, then multiplying by 100. Avg indicates the average of two means for each experimental condition.
[a] Loss experiment included low level only.

from the alveolar measurement device are shown in Table 3. The mean recoveries for the first and second runs were 104 and 102%, respectively, with the average value of the two means being 103%, thereby indicating that there was no major CO loss from the alveolar measurement device.

Table 3 also shows the results of the carryover experiments. In the low level experiment, the mean recoveries for the first and second runs were 102 and 96%, respectively, with the average value of the two means being 99%. This indicates that there were no problems associated with the carryover of CO. As such, the data from both of the above experiments reflect the good reproducibility of the proposed alveolar CO measurement system. This was further supported by the finding that the relative standard deviations (RSDs) of the data sets were less than 7% for the loss experiment and less than 8% for the carryover experiment.

Table 4. Alveolar breath CO concentrations (ppm) obtained from 10 nonsmokers using direct measurement method and bag sampling followed by dosimeter (BS & D) measurement method.

	Direct method	BS & D method
Subject ID		
1	2.4	2.6
2	3.9	3.6
3	3.1	3.2
4	3.1	3.5
5	5.0	4.6
6	4.7	5.4
7	3.3	3.5
8	3.0	3.3
9	4.0	4.2
10	3.5	3.7
Mean	3.6	3.8
S.D.	0.8	0.8

3. 4 Comparison with bag sampling-CO dosimeter measurement method

Table 4 shows the alveolar breath CO concentrations obtained from nonsmokers using the two measurement methods. The results did not differ significantly from each other, thereby indicating that the two methods were comparable for alveolar CO measurements. For the direct measurement method, the alveolar CO concentrations of the nonsmokers ranged from 2.4 to 5.0 ppm with a mean of 3.6 ppm, while for the bag sampling-CO dosimeter measurement method-the concentrations ranged from 2.6 to 5.4 ppm with a mean of 3.8 ppm.

4. DISCUSSION

The evaluations of the proposed direct alveolar CO measurement device included the following tests: (1) effect of humidity on CO measurements by CO dosimeter, (2) recovery and carryover of CO through the device, and (3) comparison of direct alveolar CO measurement method with bag sampling-CO dosimeter measurement method. The humidity test, undertaken using two different experimental methods, indicated that a humidity of up to 95% had no influence on the CO measurement of the CO dosimeter used in the cur-

rent study. This was also supported by the finding that the CO concentrations in the clean dry test air and humidified test air prepared to provide the same CO concentration were not significantly different from each other for both CO levels (1 and 40 ppm) (Table 2).

The studies designed to test the recovery and carryover of CO confirmed that the direct alveolar CO measurement device was capable of accurately measuring CO levels found in breath. The recovery test was performed by comparing the synthetic breath CO concentration at the inlet with that at the measuring port of the spirometer while a stream of synthetic breath containing 1 ppm of CO was flowing through the device. If the downstream concentration had been lower than the upstream level, this would have indicated a CO loss. However, no significant difference between the downstream and upstream concentrations was found in the current study. Meanwhile, the carryover test was conducted by measuring synthetic breath containing a low concentration of CO (1 ppm) following the measurement of a high concentration (40 ppm). If carryover had been a problem, significant recoveries exceeding 100% would have been measured for the low-level measurements. However, this was clearly not the case, thereby indicating that there were no problems associated with the carryover of CO. The recovery and carryover aspects are extremely important when actual exposure is predicted based on the measurement of CO in breath.

The direct measurement method was compared with bag sampling followed by the CO dosimeter measurement method for alveolar CO levels in nonsmokers. The alveolar CO levels measured using the two methods were not significantly different from each other, indicating that the two methods were comparable for alveolar CO measurements. This result implies that the proposed device for direct alveolar CO measurement can be applied to measure CO levels found in breath, thereby overcoming several disadvantages associated with the handling of bags, as stated in the Introduction. Furthermore, the proposed device can be employed to measure a low background breath CO concentration (even lower than 1 ppm), since the CO dosimeter has a

sensitivity of 0.1 ppm.

The direct measurement method of alveolar breath CO successfully laboratory-tested used synthetic breath containing 1 and 40 ppm CO. This test concentration range is well within the breath CO concentration range already measured for certain occupational exposure as well as non-occupational environmental exposure. For example, nonsmoking office workers have been found to have alveolar CO levels of 23 ± 3 ppm compared to levels of 8 ± 2 ppm in nonsmoking workers in other offices in the same building (Wallace, 1983). Meanwhile, the population-weighted arithmetic mean breath CO concentrations and associated standard error in Denver and Washington D.C. have been measured as 7.2 ± 0.2 and 5.1 ± 0.2 ppm, respectively (Wallace et al., 1984), while the breath CO concentrations in California range from 2.0 to 13.3 for nonsmokers and from 6.1 to 36.7 ppm for smokers (Lambert et al., 1988). Accordingly, it is suggested that the current method can be effectively applied to the measurement of certain occupational exposure as well as non-occupational environmental exposure within this breath concentration range.

5. CONCLUSIONS

A novel portable alveolar CO direct measurement device was developed and tested. The tests indicated that humidity had no influence on the CO measurements taken by the CO dosimeter used in this study, plus there were no problems associated with the recovery and carryover of CO through the device. Accordingly, it would appear that the proposed device can be effectively applied to measure CO levels found in breath, thereby overcoming several disadvantages associated with the previous bag and sampling methods. Moreover, the proposed alveolar CO measurement protocols can overcome the problems associated with transportation and laboratory gas chromatograph analyses when using adsorbent tubes for alveolar CO sampling, as reported in a recent previous study. The various advantages offered by the proposed CO measurement

protocol over previous CO measurement protocols should allow for an increase in the utilization of breath analyses for assessing CO exposure. A major limitation for the use of the current device is that the breath CO measurement should be performed at environments of lower background CO levels compared to exposure CO levels. Accordingly, a further study is suggested to develop this disadvantage.

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