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Journal of Occupational and Environmental Hygiene

Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713657996

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First published on: 09 May 2011

To cite this Article Hirst, Deborah V. L. , Gressel, Michael G. and Flanders, W. Dana(2011) 'Short-Term Monitoring of Formaldehyde: Comparison of Two Direct-Reading Instruments to a Laboratory-Based Method', Journal of Occupational and Environmental Hygiene, 8: 6, 357 — 363, First published on: 09 May 2011 (iFirst)

To link to this Article: DOI: 10.1080/15459624.2011.578499

URL: http://dx.doi.org/10.1080/15459624.2011.578499

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Journal of Occupational and Environmental Hygiene, 8: 357–363
ISSN: 1545-9624 print / 1545-9632 online
DOI: 10.1080/15459624.2011.578499

Short-Term Monitoring of Formaldehyde: Comparison of Two Direct-Reading Instruments to a Laboratory-Based Method

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Airborne formaldehyde concentrations can be measured using several different techniques, including laboratory-based methods and direct-reading instruments. Two commercially available direct-reading instruments, an RKI Instruments Model FP-30 and a PPM Technology Formaldemeter htV, were compared with National Institute for Occupational Safety and Health Method 2016 in different test environments to determine if these direct-reading instruments can provide comparable results. The methods yielded the following mean concentrations for 47 samples: NIOSH Method 2016, 0.37 ppm; FP-30, 0.29 ppm; and htV, 0.34 ppm. Results from both of the direct-reading instruments were correlated with the laboratory-based method ($R^2 = 0.78$ for FP-30, and 0.902 for htV). Comparison of the means of the three methods showed that on average the FP-30 instrument ($p < 0.001$) differed statistically from NIOSH Method 2016, whereas the htV ($p = 0.15$) was not statistically different from the NIOSH method. Sensitivity and specificity tests demonstrated that the FP-30 had sensitivity above 60% to detect formaldehyde concentrations at all the cutoff levels tested, whereas the htV appeared to have greater sensitivity above 88% for the levels evaluated.

Keywords air sampling, direct-reading monitors, formaldehyde, instrument comparison

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INTRODUCTION

Formaldehyde is used in the manufacturing of common building materials (plywood, fiberboard, oriented strand board) and many products, including paper, resins, fertilizers, cosmetics, and medications, and in household products as a preservative.(1–3) Formaldehyde is commonly released into the air by burning wood or natural gas, from cigarettes or automobiles exhaust, or by off-gassing from certain materials.(3,4) Exposure to even low levels of formaldehyde is a concern because of its potential health effects. Common health effects include eye, skin, and respiratory tract irritation.(5–7) Formaldehyde is also a suspected human carcinogen.(6,8) Concern over health effects and use in various products, particularly in home environments, has led to research on formaldehyde off-gassing rates along with developing reliable field monitoring methods to determine airborne formaldehyde concentrations.(9,10)

Airborne formaldehyde can be measured using different techniques, such as laboratory-based methods and direct-reading instruments. Direct-reading instruments provide results real-time or within a few minutes; laboratory-based methods, which necessitate sample analysis, can typically take more than a day for results. Field-based comparisons of the reliability and accuracy of direct-reading methods to a fully evaluated air sampling method for airborne formaldehyde concentrations are limited.

The objective of this study was to compare two commercially available direct-reading formaldehyde instruments with a fully evaluated laboratory method in a field application to determine whether direct-reading instruments can provide comparable results. The study compared Model FP-30 (RKI Instruments Inc., Hayward, Calif.) and the Formaldemeter *htV* (PPM Technology Ltd., Caernarfon, Gwynedd, Wales, U.K.) with NIOSH Method 2016.(11)

METHODS

Table I summarizes the three methods, and Figure 1 shows photos of the instruments.

TABLE I. Formaldehyde Method Characteristics

	Method 2016	FP-30[A]	htV[A]
Analytical technique	High-performance liquid chromatography, ultraviolet detection	Photoelectric photometry	Electrochemical
Sampling media	Silica gel cartridge coated with 2,4-DNPH	Detection tabs	None reported
Range	0.012 to 2.0 ppm for a 15 L sample	0 to 1.00 ppm	0 to 10.00 ppm
Accuracy	± 19%	± 10%	± 25%
Interferents	Ozone, ketones, other aldehydes	None reported	Phenol, resorcinol, alcohols, aldehydes, humidity >60%
Flow rate	0.030 to 1.5 L/min	0.35 L/min	0.353 L/min
Field study sample period	60 min	15 min	60 sec

Note: DNPH = 2,4-dinitrophenylhydrazine.
[A] Manufacturer's specifications.

Direct-Reading Instruments

Formaldemeter htV

The *htV* uses electrochemical sensing technology to measure airborne formaldehyde concentrations and also measures ambient temperature and relative humidity. The *htV* collects single air samples upon initiation by the user, uses a sampling frequency of 1 to 3 min, and analyzes the samples within 60 sec in high accuracy mode and 8 sec in low accuracy mode. For this study, the *htV* was used in high accuracy mode.

The manufacturer specifies that the instrument is capable of measuring formaldehyde concentrations ranging from 0 to 10.00 ppm with resolution of 0.001 ppm. Phenol is a positive interference for the *htV*.(12) To prevent potential sensor interference by phenol, samples were collected with an inline phenol filter, and every fifth sample was discarded according to the manufacturer's instructions. Although the *htV* is sensitive to high temperatures and humidity, the manufacturer reports that the instrument is specially designed to compensate for extreme relative humidity (i.e., anything outside 40–60%).(12) The instrument is also temperature compensated to operate accurately in the range of 50°–86°F.

According to the manufacturer, the *htV* monitor requires periodic calibration to guarantee the instrument is functioning properly. Between samples, the instrument's sensor is cleared once it is turned off for a few minutes and then turned on. A formaldehyde calibration standard diffusion tube,

FIGURE 1. PPM Technology Formaldemeter *htV* and RKI Instruments Model FP-30 direct-reading instruments.

thermometer, and temperature/concentration table are used to check and adjust the calibration of the instrument. With the instrument turned on and both end plugs removed from the tube, the sampling port of the instrument is firmly inserted into the sampling end of the tube. The "sample" button on the instrument is pressed, and the tube is removed after the internal sampling pump stops. After 60 sec, a formaldehyde concentration will appear on the instrument's screen. This displayed value is checked with the temperature/concentration table on the tube. Each calibration point (i.e., temperature reading) on the calibration standard corresponds to a specific concentration of formaldehyde. However, if the reading is within 10% of the value on the table, then no recalibration is needed.

Model FP-30

The FP-30 uses photoelectric photometry with colorimetric detection tabs to measure formaldehyde in air. The FP-30 draws in air with an internal pump and uses a microprocessor to control sample flow rate. The instrument uses disposable detection tabs to sample airborne formaldehyde. Number 009 detection tabs were used in this study to measure formaldehyde concentrations ranging from 0 to 1.00 ppm in a 15-min sampling time. Other detection tabs for the instrument include number 008 for 0 to 0.40 ppm in a 30-min sampling time and number 010 for 0 to 0.06 ppm in a 3-min sampling time. According to the manufacturer, the FP-30 is capable of measuring formaldehyde concentrations ranging from 0 to 1.00 ppm with a resolution of 0.01 ppm. Measurements are reportedly accurate to ± 10% when air temperature is between 14°F and 104°F and the relative humidity is below 90%.(13) If a high concentration of gas is encountered, the instrument has a 10-min purge cycle that clears the sensor for the next reading. According to the manufacturer, the instrument needs to be factory calibrated every 5 years.

Laboratory-Based Method

NIOSH Method 2016 was used as the reference method for comparison of the two direct-reading instruments. This method was previously (1998) fully evaluated by NIOSH, which included testing to quantify storage stability, collection efficiency, and breakthrough volumes.(14) The NIOSH accuracy criterion requires that a method should have 95% probability of providing a concentration measurement within ± 25% of the true concentration. Method 2016 requires that air samples be collected using a cartridge containing silica gel coated with 2,4-dinitrophenylhydrazine (2,4-DNPH).

For this study, samples were collected on Supelco S10 LpDNPH cartridges (model #S10L, lot #SP9984; Sigma-Aldrich, St. Paul, Minn.). Because ozone can consume the 2,4-DNPH reagent and degrade the formaldehyde derivative,(11) a Supelco LpDNPH ozone scrubber was used with each air sample cartridge. The ozone scrubber was connected upstream of the S10L cartridge, which was connected via plastic tubing to the inlet port of an SKC AirCheck 2000 sampling pump (SKC Limited, Harrisburg, Pa.). All SKC AirCheck 2000 pumps were calibrated with a Bios DryCal DC-Lite (BIOS, Butler, N.J.) to a nominal flow rate of 0.5 L/min. Multiple samples were collected with the same pumps throughout the day.

Each collected sample and field blank were immediately capped and placed in individual metalized packaging to protect the media from air, moisture, and light. The ozone scrubbers were discarded after each sample. At the end of each sampling day, the samples and field blanks were shipped on ice (0°C), according to the method, to the contracting laboratory for analysis. Pre- and post-sampling pump flow calibration checks were performed at the beginning and end of the sampling day.

Test Environment and Procedure

Sexton et al.(10) have suggested that manufactured homes and similar structures are an appropriate environment for conducting a study comparing two direct-reading instruments because of the measurable amounts of formaldehyde in the units. For convenience and access to different types of temporary housing units (THUs), this study was conducted at the Federal Emergency Management Agency (FEMA) storage site in Selma, Alabama.

The particular THUs selected at the site were based on convenience of access for sampling. Makes and models of the THUs are not provided because they were not relevant to the purpose of this study. The THUs served only as a test environment for the three formaldehyde sampling methods. The THUs were not occupied and were not scheduled to be used in the future. Sampling personnel remained in the THUs for the duration of each sample and wore suitable respiratory protection.

Samples for formaldehyde were collected over a 3-day period. All three formaldehyde sampling methods (i.e., sample set) were simultaneously started within 1 minute of entering each THU. The sampling methods were side-by-side in each THU. Each sampling set was 60 min. At the completion of this study, a total of eight sampling pumps, five FP-30 instruments, and seven *htV* instruments were used to sample in the THUs. There were no inter-instrument comparisons made in this study. Because of the differences in the operation of the instruments, NIOSH Method 2016, the FP-30, and the *htV* collected a different number of samples during the 1-hr sampling period. Three 15-min samples for formaldehyde were collected using the FP-30, and the means for each set of three samples were used in the analysis. A 60-sec sample was collected every 12 min using the *htV* for a total of five samples. The means for each set of five samples were used in the analysis. One 60-min Method 2016 sample was collected.

Data Analysis

Data were analyzed using descriptive statistics, including means, medians, standard deviations, and minimum and maximum values. Paired t-tests were used to compare the mean differences between the methods. The association between Method 2016 and the two direct-reading instruments was assessed by bivariate scatter plots, Bland-Altman plots, correlation analyses, and linear regression. Sensitivity and specificity of the two direct-reading instruments were assessed to detect a level above one of the arbitrary values by using the results from Method 2016 as the reference concentration. The sensitivity is the probability of the direct-reading instrument indicating that a concentration is above one of the arbitrary values for one that is above the arbitrary value according to Method 2016, whereas the specificity is the probability of the instrument indicating that a concentration is below one of the arbitrary values for one that is below the arbitrary value according to the NIOSH method.

For the sensitivity and specificity tests, 0.1, 0.2, and 0.3 ppm were chosen as the arbitrary cutoff values. Since the observations were clustered at and below 0.2 ppm on the scatter plots, 0.2 ppm was chosen as one of the values for calculating sensitivity and specificity calculations. The 0.2 ppm value is greater than 0.1 ppm but less than the threshold limit value (TLV®) ceiling of 0.3 ppm recommended by the ACGIH® for formaldehyde.(8)

Regression diagnostics included evaluation of higher order terms, use of condition indices to assess potential collinearity, and residual plots. In sensitivity analyses, results analyzed using log-transformation obtained qualitatively similar results as those without the transformation. All analyses were done in Microsoft Excel 2003 (Microsoft Corp., Redmond, Wash.) and SAS 9.1 (SAS Institute Inc., Cary, N.C.).

Based on the W-test of log-transformed concentration data, the data distribution of the samples analyzed using Method 2016 was determined to be approximately lognormal ($p = 0.961$). The geometric mean and geometric standard deviation were 0.245 and 2.59 ppm, respectively. The LOD was 2.0 ppb with a 28 L average sample volume collected over 1 hr.

RESULTS

A total of 72 sample sets were collected using each of the three sampling methods. Only 47 sample sets were included in the analysis because some of the sampling pumps used for Method 2016 had pre- and post-sampling flow rate differences greater than 10%. To address this flow rate problem, only the first and last samples of a sequence of samples (i.e., collected on the same day) from the same pump with greater than 10% difference in pre- and post-sampling flow rates were included in the analysis. The concentration for the first sample was calculated using the pre-sampling flow rate, while the concentration for the last sample was calculated using the post-sampling flow rate. All other samples with flow rate differences of 10% or less were included in the analysis using the mean of the pre- and post-sampling flow rates. There were no NIOSH method sample results below the LOD of the 47 sample sets.

Table II shows the 47 sample sets that were used for data analysis. Table III presents descriptive statistics for each

TABLE II. Sampling Methods Data

Day	Method 2016	FP-30[A]	*htV*[A]
Day 1	1.1	1.0	0.71
Day 1	0.026	0.040	0.036
Day 1	0.029	0.013	0.032
Day 1	0.28	0.13	0.27
Day 1	0.77	1.0	0.78
Day 1	0.36	0.23	0.39
Day 1	0.15	0.10	0.22
Day 1	0.14	0.10	0.24
Day 1	0.17	0.13	0.17
Day 1	0.52	0.47	0.49
Day 1	0.93	0.56	0.62
Day 1	0.96	1.0	0.84
Day 1	1.5	1.0	1.2
Day 1	0.053	0.030	0.13
Day 2	0.18	0.10	0.26
Day 2	0.15	0.090	0.18
Day 2	0.19	0.11	0.24
Day 2	0.95	1.0	0.66
Day 2	0.73	0.77	0.56
Day 2	0.26	0.19	0.29
Day 2	0.40	0.27	0.35
Day 2	0.88	0.89	0.56
Day 2	0.74	0.41	0.45
Day 2	0.22	0.073	0.16
Day 2	0.25	0.11	0.19
Day 2	0.57	0.18	0.41
Day 2	0.79	0.27	0.81
Day 2	0.089	0.037	0.17
Day 2	0.24	0.080	0.25
Day 2	0.12	0.050	0.19
Day 2	0.18	0.050	0.29
Day 2	0.14	0.047	0.21
Day 2	0.79	0.63	0.47
Day 2	0.21	0.14	0.34
Day 2	0.18	0.15	0.19
Day 2	0.34	0.30	0.37
Day 3	0.060	0.040	0.16
Day 3	0.083	0.47	0.18
Day 3	0.15	0.43	0.12
Day 3	0.35	0.19	0.28
Day 3	0.15	0.040	0.19
Day 3	0.10	0.027	0.18
Day 3	0.22	0.077	0.29
Day 3	0.12	0.043	0.21
Day 3	0.13	0.043	0.22
Day 3	0.23	0.15	0.16
Day 3	0.19	0.13	0.23

[A] Means for each set of three samples for the FP-30 and means for each set of five samples for the *htV*.

TABLE III. Sample Sets Used for Data Analysis

Method Paired Triplets	n[A]	Mean (SD) (ppm)	Mean Difference vs. NIOSH (SD) (ppm)	Median Difference (ppm)	Range (ppm)	Max-Min Difference (ppm)	Mean[B] Squared Error
Method 2016	47	0.37(0.35)	—	0.22	0.026–1.5	1.5	—
FP-30	47	0.29(0.32)	0.09(0.16)	0.07	0.01–1.00	0.99	0.03
htV	47	0.34(0.24)	0.03(0.14)	−0.02	0.032–1.22	1.188	0.019

[A] Number of samples.
[B] NIOSH as the reference value for this analysis.

sampling method. Model FP-30 data ranged from 0.01 to 1.00 ppm, the upper limit for the monitor, with a mean of 0.29 ppm. Formaldemeter *htV* data ranged from 0.032 to 1.22 ppm with a mean of 0.34 ppm. Method 2016 data ranged from 0.026 to 1.5 ppm with a mean of 0.37 ppm. The FP-30 and Method 2016 had a mean difference of 0.09 ppm ($p = 0.0007$), while Method 2016 and the *htV* had a mean difference of 0.03 ppm ($p = 0.15$).

Figure 2 shows the relationship between the direct-reading instruments and Method 2016 for the 47 discrete integrated samples, along with a 1:1 hypothetical line of how either instrument would perform if it matched the laboratory method perfectly. The overall research findings did not change when the mean flow rate value for each sample set was applied to the original 72 sample sets. Summary statistics for the original 72 samples are shown in Table IV.

Five sample results from the FP-30 were recorded as 1.00 ppm, the maximum for the monitor. If these five sample results from the FP-30 and the associated data points from Method 2016 and *htV* are excluded from the analyzed data set, then the mean values for the 42 observations for Method 2016, FP-30, and *htV* methods are 0.29, 0.20, and 0.281 ppm, respectively (Table V).

Temperature and Relative Humidity

Temperatures in the THUs ranged from 80°–102°F with an average temperature of 89°F. Relative humidity ranged from 50–83% with an average reading of 67%. Relative humidity was positively associated with formaldehyde concentrations for all three methods, whereas ambient temperature was negatively associated with the measured concentrations.

Sensitivity and Specificity

For the purpose of this study, sensitivity and specificity were defined using three arbitrary cutoff values. For 0.1 ppm, the FP-30 and *htV* had 68% and 100% sensitivity, and 86% and

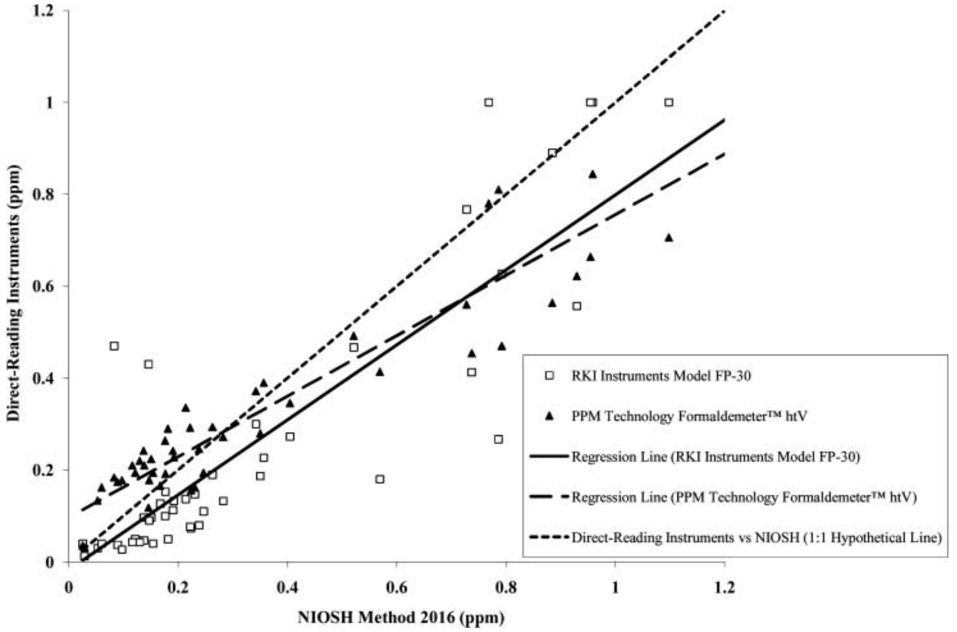

FIGURE 2. Relationship between the direct-reading instruments and NIOSH Method 2016. FP-30, $R^2 = 0.78$; *htV*, $R^2 = 0.902$.

TABLE IV. Statistics for Sampling Methods

Method Paired Triplets	n	Mean (SD) (ppm)	Mean Difference vs. NIOSH (SD) (ppm)	Min / Max (ppm)
Method 2016	72	0.37(0.34)	—	0.0014/1.5
FP-30	72	0.26(0.29)	0.11(0.050)	0.013/1.00
htV	72	0.349(0.250)	0.0210(0.0900)	0.0320/1.270

28% specificity, respectively. For 0.2 ppm, the FP-30 and *htV* had 60% sensitivity and 91% specificity, and 88% sensitivity and 59% specificity, respectively. For 0.3 ppm, the FP-30 and the *htV* had 65% and 94% sensitivity, and 92% and 97% specificity, respectively. Table VI shows the sensitivity and specificity results for all three cutoff values.

DISCUSSION

Under the environmental conditions of this field study in THUs, the means of the integrated formaldehyde measurements obtained using the direct-reading instruments were positively correlated with single measurements obtained over the same time period using NIOSH Method 2016 ($R^2 = 0.78$ for the FP-30 and 0.902 for the *htV*). However, the FP-30 method ($p < 0.001$) yielded statistically significantly lower readings than Method 2016, whereas the differences, with the *htV* ($p = 0.15$) were not statistically significantly different from Method 2016.

The estimated sensitivity and specificity varied for each instrument depending on the level (0.1, 0.2, 0.3 ppm) that a user felt was important to detect. In general, the FP-30 had approximately the same sensitivity at all the cutoff levels tested. The *htV* appeared to have sensitivity above 88% for the levels evaluated, but its specificity was low at lower levels (i.e., 0.1 and 0.2 ppm). The sensitivity and specificity were estimated by treating the results from Method 2016 as the reference concentration. Since there is some uncertainty in the NIOSH method (i.e., accuracy is ± 19%) the sensitivity and specificity estimates can be viewed as having some uncertainty but nevertheless should provide approximate estimates.

One potential drawback of the FP-30 monitor is its inability to report formaldehyde concentrations greater than 1.00 ppm. In some applications this could be a major concern, but for screening to detect occupational exposure levels (e.g., greater than 0.2 ppm), this should pose little or no problem. The monitor displays and stores a reading as "over," if the concentration measured is greater than 1.00 ppm. Five sample results that had an "over" reading were recorded as 1.00 ppm. If these five sample results from the FP-30 and the associated data points from Method 2016 and the *htV* are excluded from the analyzed data set, then the mean values for the 42 observations for the NIOSH method, the FP-30, and *htV* methods are 0.29, 0.20, and 0.281 ppm, respectively. The exclusion of the five data points had no large impact on the comparison of the three methods.

The *htV* was calibrated each day in the morning when temperatures and relative humidity were within the recommended parameters. Because both temperature and relative humidity were above the favorable operating range, the reliability of the *htV* instrument's high formaldehyde readings was a concern. The highest temperatures in this field study were outside the recommended range of 59°–84°F and could affect the accuracy of the thermometer supplied with the *htV* monitor. Accurate readings from the thermometer are needed because formaldehyde concentrations in the calibration standard vary with temperature.(12) This temperature difference was a weakness for this field study because, according to the temperature/concentration table, a one-degree change in temperature can mean a 10% difference in concentration at every temperature from the calibration diffusion tube.

There is also some ambiguity with the NIOSH method results that suggests breakthrough might have occurred. Two of the samples analyzed were above the validated range (about 0.006 to 1.0 ppm) for a 30-L sample. Two samplers in series would have been used in the field study if it was suspected that breakthrough might occur. If formaldehyde broke through the first sampler, the second sampler would have trapped the formaldehyde that had broken through.

Another weakness of this study was not using 25 of the 72 sample results in the analysis because of sampling pump calibration problems. According to the *NIOSH Manual of Analytical Methods*, the flow rate should be within ± 5% of the target flow rate.(15) For this study, data within ± 10% of the 0.5 L/min target flow rate were used for analysis; this discarded 35% of the data. However, if ± 5% of the target flow rate was

TABLE V. Statistics for Sampling Methods for Sample Results >1

Method Paired Triplets	n	Mean (SD) (ppm)	Mean Difference vs. NIOSH (SD) (ppm)	Min / Max (ppm)
Method 2016	5	1.1(0.29)	—	0.77/1.5
FP-30	5	1.00(0.00)	0.10(0.29)	1.00/1.00
htV	5	0.843(0.222)	0.257(0.068)	0.664/1.220

TABLE VI. Sensitivity and Specificity Calculations for FP-30 and *htV*

Method	Arbitrary Cutoff	Sensitivity	Specificity
FP-30			
	0.1 ppm	0.68	0.86
	0.2 ppm	0.60	0.91
	0.3 ppm	0.65	0.92
htV			
	0.1 ppm	1.00	0.28
	0.2 ppm	0.88	0.59
	0.3 ppm	0.94	0.97

used as the cutoff, more than 35% of the data would have been discarded. Loss of data could have been prevented if flow rates had been checked at the beginning and end of each sample rather than at the beginning and end of each sampling day. Sampling pump calibration problems decreased the sample size and lessened the ability to detect statistical differences between the sampling methods.

This study had a few weaknesses with instrument sensitivity to high humidity and temperatures, possible breakthrough, and pump calibration flow rates. The lack of control of the true formaldehyde concentration so that the sensitivity and specificity of the three methods could be better compared was also a limitation. However, despite these issues, this field study provided a realistic test environment to compare the different methods.

CONCLUSIONS

Under the field conditions that existed during this study, the Model FP-30 yielded statistically significantly different formaldehyde concentrations from NIOSH Method 2016 ($p < 0.001$), whereas the Formaldemeter *htV* was not statistically significantly different from Method 2016 ($p = 0.15$). High temperature and relative humidity readings, the direct-reading instruments' operating capability and environment sensitivity, and uncertainty in the NIOSH method may have affected the relationship between the instruments and Method 2016. Based on sensitivity and specificity tests, the FP-30 had sensitivity above 60% to detect formaldehyde concentrations at all the cutoff levels tested, whereas the *htV* appeared to have greater sensitivity above 88% for the levels evaluated.

The two direct-reading instruments correlated with the laboratory-based Method 2016. Laboratory analysis can be expensive, whereas direct-reading instruments may be useful as screening tools and might preclude the need to wait for sample results if very low or very high concentrations are measured. However, additional field evaluations under a variety of environmental conditions and formaldehyde concentrations are needed to better understand the accuracy of these direct-reading instruments as compared with NIOSH Method 2016.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the significant collaboration of the CDC and Bureau Veritas North America for this work. Field guidance, data collection, and data analysis were provided by Chad Dowell, Gary Noonan, David Olson, Liane Hostler, Rick Aspray, Ronald Dobos, William Dendy, Paul Epstein, Laurence Reed, Sam Tucker, Stan Shulman, Kevin Ashley, Dan Farwick, Kevin H. Dunn, Dave Marlow, Brenda Jones, Ellen Galloway, Paula O'Connor, Debbie Fite, Teresa Lewis, Gregory Burr, Erik Devine, Jennifer Roberts, Donald Booher, and Karl Feldmann The authors also appreciate the guidance of peer reviewers Aaron Sussell and Lynn Wilder. Field site assistance was provided by Ronald Parten, Randy Brown, and other site personnel.

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