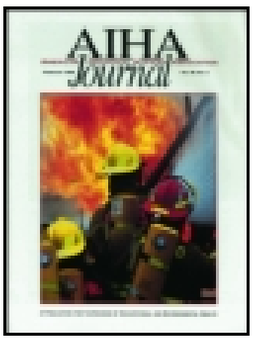

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Performance of Electronic Flow Rate Meters Used for Calibration of Air Sampling Pumps

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Electronic flow rate meters (EFRMs) have been used by industrial hygienists for more than 20 years and are useful because they reduce the time required to calibrate air sampling pumps. This study compared the variability of the traditional bubble burette meter with electronic flow meters and simultaneously compared several EFRMs under different calibration conditions. The flow rates of air sampling pumps were set using a standard bubble burette meter at flow rates of 2 or 50 mL/min using two pressure drops, 2 inches water and 10 inches water. Four airflow rate meters (Bios DryCal™, A.P. Buck mini-Buck™, MSA Accuflow™, and Sensidyne Gilibrator™) were concurrently compared at each of the pump flow rate and pressure drop combinations. Results indicated that the standard bubble burette method is more variable than the EFRMs and that the flow rates given by the EFRMs were significantly different ($p<0.0001$) at both the high and low flow rates. Although the calibrators gave significantly different flow rates, the difference was within the acceptable air sampling pump error of ±5%.

Keywords: air sampling pump calibration, electronic calibration devices, electronic flow rate meter

Industrial hygienists routinely sample to determine the identity and quantity of airborne agents in occupational and environmental settings. The information gathered from this process is used for a variety of purposes, such as assessing compliance with occupational exposure standards, evaluation of effectiveness of controls, selecting the appropriate personal protective equipment, and identifying where engineering controls are needed. [1] The traditional method of exposure assessment from the inhalation route uses active or passive sampling methods. Active sampling differs from passive sampling by using an air-moving device (pump) to collect from a known volume of air over time, whereas passive samplers rely on a known diffusion rate of contaminant into the sampler.

When active samples are taken, the volume of air collected must be known to accurately determine the concentrations of airborne contaminants (units of either mass or volume of the contaminant per total volume of the air collected). Typically, the mass collected during sampling is determined by laboratory analysis. However, the individual collecting the sample controls the duration of the sampling period and the calibration of the flow rate of the sampling device, which are used to determine the sample volume using Equation 1[2]:

$$\text{Sample Volume (V)} = \text{Flow Rate (L/min)} \times \text{Sample Time (min)} \quad \textbf{(1)}$$

The accuracy of the exposure estimate depends on the accuracy of the reported sample volume collected. Inaccurate calibration leads to incorrect reporting of worker exposures and inefficient use of resources.[3] Consequently, samples taken to estimate the airborne exposure are only as reliable as the calibration of the equipment used to collect the samples.

Air sampling pump calibrators can be divided into two categories: primary calibrators and secondary calibrators. Primary calibrators measure volume based on the measured dimensions of a physical space, which are traceable to an international or national standard.[4] Secondary standards are considered reference instruments that trace their calibration to primary standards.[1] Primary calibrators include the bubble burette and spirometer; manufacturers of electronic flow

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meters also claim their instruments are primary calibrators. The rotameter and orifice meter are examples of the secondary calibrators that are available for use in calibrating air sampling pumps.

In today's demanding work environments, industrial hygienists find ways to efficiently use their time. The bubble burette, historically used as the primary means of calibrating air sampling pumps, is time-consuming and subject to operator errors in manually turning the timer on and off, and in determining when the bubble passes a mark on the burette.[2] The demand for faster, more reproducible techniques to calibrate air sampling pumps led to the development of electronic bubble meters.

Electronic flow rate meters (EFRMs) generally use small, fixed-volume chambers and infrared sensors connected to a timer, which decrease the amount of time to set and calculate the flow rate of air sampling pumps. Additionally, many EFRMs provide a means to print data. Because of the reduced calibration time, ease of use, and perceived accuracy, the demand for electronic bubble meters has increased. Although these instruments are commonly used in industrial hygiene, no literature could be found comparing them to the standard bubble burette method or to other EFRMs.

The purpose of this study was to compare the variability in the bubble meter method with the variability in EFRMs, and to determine whether the EFRMs provide the same flow rate estimate. The flow rate meters were compared at all combinations of two flow rates and two pressure drops. The results should help IHs to better understand the performance and limitations of EFRMs.

MATERIAL AND METHODS

Materials

A bubble burette meter was set up as described in the *OSHA Technical Manuals,* and two identical units from each of four manufacturers were used: the Bios International DryCal™ DC-1 (Pompton Plains, N.J.); the A.P. Buck mini-Buck Calibrator™ (Orlando, Fla.); the MSA Accuflow™ Digital Flow Indicator (Pittsburgh, Pa.); and the Sensidyne Gilibrator™ (Clearwater, Fla.). Each of the units had been certified by the manufacturer within the previous year. The mini-Buck, the Accuflow, and the Gilibrator use a soap similarly to the bubble burette method. Each has two distinct parts, a flow cell and a control unit. The flow cell produces a bubble that travels up it under negative pressure when an air sampling pump is connected. The time required for the bubble to travel a preset distance, which is a known volume, is measured by a pair of infrared sensors mounted on the flow cell. The distance the bubble travels is set by the location of the two infrared sensors, and the volume is determined by the distance traveled and the cross-sectional area of the bubble tube. As the bubble travels through the sensor zone, the sensors are triggered, providing the time required for the bubble to travel the known volume. This information is sent to a microprocessor in the control unit. The flow rate is then calculated from the division of the volume by the time, and is displayed on an LCD panel.

The DryCal, like the other three electronic bubble meters, is a primary airflow calibrator. Rather than using a soap solution to generate a bubble that is used to measure the flow rate, the DryCal uses a frictionless graphite composite piston. The operator presses the "Read" button on the base of the calibrator to set the piston in motion. The piston is allowed to accelerate for a short period before the flow rate is calculated. A finely collimated light beam is broken by a precision encoder attached to the piston. The time between the breaks of the light beam is measured and used by the internal computer to calculate the volumetric flow rate as for the other three.

A Du Pont P-2500 constant flow sampler (Wilmington, Del.) and a Du Pont P200 A constant flow sampler were used for high (2 L/min) and low (50 mL/min) flow rates, respectively. A Dwyer magnehelic was used to generate a pressure drop across the pump.

Experimental Design

The variability of the bubble burette was compared with the variability of the Bios EFRM by setting four pumps at a high flow rate (approximately 2 L/min) and four pumps at a low flow rate (approximately 50 mL/min), attaching the pumps to the flow rate meter with no additional pressure drop in line, and recording 10 measurements using the Bios, then recording 10 readings using the bubble burette method. Times for the bubble meter were measured with a Micronta LCD quartz stopwatch, serial number 3A8.

Flow rate measurements using four electronic calibrators were evaluated at four combinations of flow rate and pressure drop (2 L/min and 2 inches H_2O; 2 L/min and 10 inches H_2O; 50 mL/min and 2 inches H_2O; 50 mL/min and 10 H_2O). The experimental or nominal flow rates of 2 L/min and 50 mL/min were set by the bubble burette method following the method described in the *OSHA Technical Manuals.*[5] Flow measurements were obtained from the electronic calibrators placed in series. Position in the serial calibration train was randomized, and an equal number of observations (15) was obtained from each EFRM at each position. The exception was the MSA Accuflow; it had to be in the first position (furthest from the pump) during all trials because the bubble was generated from a squeeze bulb, which did not allow calibrators to be connected in series behind it. Two identical calibrators of the same type (i.e., different serial numbers) were used an equal number of times at the high flow rate to compare flow rate measurements between different units of the same model and manufacturer for BIOS, Buck, and Gilibrator devices. To minimize potential pressure and temperature variations that could affect the measurements, all measurements were made and recorded by one experimenter in the same laboratory. All high-flow calibrations were made on one day, and all of the low-flow calibrations were made on a second day. Different photodetection cells were used on the DryCal and the Gilibrator to make measurements at the high- and low-flow experimental conditions.

The air-sampling pumps were turned on and allowed to run for 5 to 10 min before the flow rate was set with the bubble burette meter. The air sampling pump was attached to a magnehelic and then in series to the bubble burette meter. The pump was then adjusted to provide a flow rate of approximately 2 L/min or 50 mL/min using the bubble burette. Then the four electronic flow meters were attached in series to the magnehelic and the air sampling pump. One person recorded 15 flow rate readings for each calibrator at each combination of flow rate, calibrator position, and pressure drop. The readings were taken as close to simultaneously as possible from each calibrator.

Data Analysis

Descriptive measures of flow rate, including mean, standard deviation, median, and range, were calculated at each nominal flow rate (50 mL/min and 2 L/min) by EFRM, serial number, pressure drop, and position of calibrator in the serial calibration train. Precision for each combination of EFRM was defined as the relative standard deviation (ratio of the standard error to the sample mean).

TABLE I. Summary Statistics of Measured Flow Rate by Device for Each Level of Nominal Flow Rate

Experimental Conditions	Flow Measure[A]	Device	
		Buret	BIOS
2 L/min	N	40	40
	mean	1.96	2.01
	% difference	2.50	
	std dev	0.02	0.01
	RSD	0.8%	0.6%
	p-value	($p < 0.0001$)	
50 mL/min	N	40	40
	mean	51.2	49.9
	% difference	2.6	
	std dev	0.4	0.2
	RSD	0.8%	0.4%
	p-value	($p < 0.0001$)	

[A]RSD = relative standard deviation (Std Dev/Mean). *p*-value for test of significant difference of flow rate between different devices.

Statistical tests for significant differences in flow rates among levels of the various experimental design factors were conducted in a hierarchical manner at each nominal flow rate. First, for each combination of flow rate and pressure drop a generalized linear model (GLM) procedure was used to test for significant differences in flow rate among positions in the calibration train. Next, a GLM was used to compare mean flow rates between different units (i.e., by serial number) of the same device controlling for position. Note that this aspect of the experimental design was conducted only at the 2 L/min nominal flow rate. Last, a GLM was used to evaluate mean flow rates among the 4 types of EFRMs controlling for position (Equation 2).

$$F_{Q,dP} = \beta_0 + \beta_1 \text{ Device} + \beta_2 \text{ Position} + \epsilon \quad \textbf{(2)}$$

where $F_{Q,dP}$ = measured flow rate at nominal flow (Q) 50 mL/min or 2 L/min and pressure drop (dP) 2 inches H_20 or 10 inches H_2O Device = a categorical variable for device with four levels: Dry-Cal, mini-Buck, Sensidyne, and AccuFlow Position = a categorical variable for position in calibration train with four levels: 1, 2, 3, and 4 β_0—β_2 = coefficient estimates for intercept and effect of independent variables ϵ = error term

RESULTS

The summary statistics for measured flow rates using the bubble burette and Bios EFRM simultaneously are presented in Table I. The precision of the bubble burette method is less than the EFRM by 25–50% as measured by the relative standard deviation.

Summary statistics for measured flow rate by position in the serial calibration train are presented in Table II for each combination of nominal flow rate and pressure drop. At the high flow rate (2 L/min), measured flow did not vary significantly (*p7*gt; 0.05). At the low flow rate (50 mL/min), the mean measured flow varied by approximately 0.5 mL/min among positions at both levels of pressure drop. Mean flow rates among positions were statistically significantly different with flow in Position 4 greater than flow in Positions 2 and 3 at both levels of pressure drop. Consequently, position was included as a variable in subsequent GLM analyses to control for its influence on measured flow rates.

Flow rates measured by different units of the same manufacturer at a nominal flow of 2 L/min and pressure drops of 2 inches and 10 inches H_20 are summarized in Table III. For the MSA EFRM, mean flow rates differed by 0.02–0.04 L/min between the two units at 2 inches and 10 inches H_2O, respectively, which was statistically significant ($p<0.0005$). For the Bios EFRMs, mean flow rates differed by 0.04–0.05 L/min between the two units and were statistically significantly different ($p<0.0001$) at each level of pressure drop. Flow rates did not differ significantly between the two Buck EFRMs at either pressure drop. Differences between mean flow rates measured by the two Sensidyne EFRMs were 0.04–0.05 L/min and were statistically significantly different ($p<0.0001$).

The mean flow rate by EFRMs for each combination of nominal flow rate and pressure drop is shown in Table IV. In the high-flow tests, mean flow rates differed by as much as 0.07 and 0.08 L/min between the Buck and MSA at 2 inches H_2O and 10inches H_2O pressure drop, respectively. In the low flow tests, the Bios EFRM gave the lowest flow rate at each pressure drop and the Sensidyne EFRM gave the highest flow rate at each pressure drop. The GLM analyses indicate that mean flow rates were significantly different among EFRMs at each experimental condition.

TABLE II. Summary Statistics of Measured Flow Rate by Position in Serial Calibration Train for Each Combination of Nominal Flow Rate and Pressure Drop

Experimental Conditions[A]	Flow Measure	Position			
		1[B]	2	3	4
2 L/min, 2 inches H_2O	N	—	180	180	180
($p = 0.6475$)	mean	—	1.95	1.95	1.96
	std dev	—	0.03	0.03	0.02
2 L/min, 10 inches H_2O	N	—	180	180	180
($p = 0.4480$)	mean	—	2.00	2.00	2.00
	std dev	—	0.05	0.03	0.04
50 mL/min, 2 inches H_2O	N	—	90	90	90
($p < 0.0001$)	mean	—	50.29	50.42	50.74
	std dev	—	0.80	0.83	0.42
50 mL/min, 10 H_2O	N	—	90	90	90
($p = 0.0002$)	mean	—	49.45	49.62	50.04
	std dev	—	0.85	1.22	0.75

[A]*p*-value for test of significant difference of mean flow rate among positions is shown below the label for each experimental condition.
[B]Not applicable because the MSA AccuFlow was always in Position 1.

TABLE III. Summary Statistics of Measured Flow Rate by Device and Serial Number for Each Level of Pressure Drop at the High Flow Rate

Experimental Conditions	Flow Measure[A]	Electronic Flow Rate Meter and Serial Number							
		MSA		BIOS		Buck		Sensidyne	
		431525	451241	B-1537	B-1556	M-2414	M-3017	14493	73227
2 L/min, 2 inches H_2O	N	90	90	90	90	90	90	90	90
	mean	1.91	1.89	1.92	1.96	1.97	1.97	1.98	1.94
	std dev	0.03	0.03	0.02	0.04	0.02	0.01	0.03	0.01
	% difference	1.0		2.0		0.0		2.0	
	p-value	($p = 0.0005$)		($p < 0.0001$)		($p = 0.1528$)		($p < 0.0001$)	
2 L/min, 10 inches H_2O	N	90	90	90	90	90	90	90	90
	mean	1.96	1.92	1.95	2.00	2.01	2.02	2.03	1.98
	std dev	0.04	0.03	0.03	0.03	0.03	0.02	0.03	0.05
	T difference	2.0		2.5		0.5		2.5	
	p-value	($p < 0.0001$)		($p < 0.0001$)		($p = 0.1641$)		($p < 0.0001$)	

[A]P-value for test of significant difference of the flow rate between different serial numbers of each device is shown.

DISCUSSION

EFRMs have many advantages over the standard bubble burette meter for calibrating air sampling pumps. They can calibrate them in a fraction of the time and more precisely than a bubble burette meter and are also more portable. The DryCal is even more convenient than the other EFRMs because it does not use a soap bubble, eliminating the need for a soap solution.

Although the EFRMs give significantly different estimates of the flow rate, the errors are within the acceptable range. The manufacturers of EFRMs advertise that their products estimate the flow rate of an air-sampling pump with little error. Each of the four manufacturers report the accuracy of their EFRMs as a percentage error from a known flow rate, usually the flow rate determined by the bubble burette method. The flow rate determined from the bubble burette meter is typically considered to have an error of ±2%. The Accuflow, DryCal, mini-Buck, and Gilibrator have reported percentage errors of ±5%, ±2%, ±2% and ±2%, respectively. The difference in flow rates between EFRMs of the same manufacturer ranged from 1 to 2.5%, and the largest difference across all EFRMs within the same flow rate/pressure drop group was 3.7% (Bios B-1537 vs. Sensidyne 14493 at 2 L/min and 10 inches H_2O). These differences are within the errors reported by the manufacturers. The MSAs were not included in this comparison because of the potential for position effect.

Another potential source of error is the vapor pressure exerted by water evaporating from the bubble as it moves up the cylinder. Errors of 1 to 3% on the high side are reported as possible for EFRMs that use soap bubbles. Even when the flow rates are adjusted down by 3%, the interpretation remains the same; the flow rates are within the errors reported by the manufacturers.

The potential effects of different EFRMs is illustrated in Table V. The two EFRMs were assumed to have been used for the same air-sampling pump, and the pump was used to monitor for exposure to particulates not otherwise classified (PNOC). The weight on the sample was assumed to be reported from the laboratory as 14.4 mg. Calculating the exposure by dividing the sample weight by the total volume, the Bios would give 15.4 mg/m³ as the 8-hour time-weighted average (TWA) exposure, whereas the Sensidyne would give 14.8 mg/m³ as the 8-hour TWA exposure. If the calculated result alone was reported, it could be interpreted that the Bios result was greater than the Occupational Safety and Health Administration's permissible exposure limit (PEL) for PNOC of 15 mg/m³[6] and actions to reduce exposure are required, whereas the Sensidyne result could be interpreted as below the PEL and not require action. However, proper interpretation of the data requires the calculation of the confidence limits, which include the sampling and analytical error, of which the calibration error is a part. When the sampling and analytical errors are considered, the interpretation of the result from both EFRMs

TABLE IV. Summary Statistics of Measured Flow Rate by Each Electronic Calibration Device for Each Combination of Nominal Flow Rate and Pressure Drop

Experimental Conditions[A]	Flow Measure	Electronic Flow Rate Meter			
		MSA	BIOS	Buck	Sensidyne
2 L/min, 2 inches H_2O	N	180	180	180	180
($p < 0.0001$)	mean	1.90	1.94	1.97	1.96
	std dev	0.03	0.03	0.02	0.03
2 L/min, 10 inches H_2O	N	180	180	180	180
($p < 0.0001$)	mean	1.94	1.98	2.02	2.00
	std dev	0.04	0.04	0.02	0.04
50 mL/min, 2 inches H_2O	N	90	90	90	90
($p < 0.0001$)	mean	50.37	49.86	50.64	50.94
	std dev	0.59	0.63	0.56	0.53
50 mL/min, 10 inches H_2O	N	90	90	90	90
($p < 0.0001$)	mean	49.90	49.02	49.84	50.24
	std dev	1.12	1.03	0.75	0.74

[A]*p*-value for test of significant difference of mean flow rate among devices is shown below the label for each experimental condition.

TABLE V. Demonstration of Potential Outcome for the Same Pump Using the Highest and Lowest Reported Flow Rates

	Calibrator[A]	
	Bios B-1537	Sensidyne 14493
Mean flow (L/min)	1.95	2.03
Sample time (min)	480	480
Calculated sample volume (m^3)	0.936	0.974
Weight on sample (mg)	14.4	14.4
Concentration (mg/m^3)	15.4	14.8
Sampling and analytical error	0.1	0.1
95% upper confidence limit (mg/m^3)	17.3	16.0
95% lower confidence limit (mg/m^3)	14.2	13.1

[A]MSA calibrators were not used because of potential position effect.

is that the exposure cannot be determined with 95% certainty to be either over or under the PEL. Of course, good industrial hygiene practice would suggest that controls to reduce exposure should be implemented.

Disadvantages of the EFRMs include the initial purchase cost and periodic maintenance. EFRMs typically cost from $900 to $1300 depending on the manufacturer. Calibration typically costs as much as $200 annually. For an industrial hygienist who does not perform a large number of air samples during a year, the purchase and upkeep cost of an electronic bubble meter versus a $200 bubble burette meter, with no upkeep cost, may not be the best use of funds.

CONCLUSION

The variability of flow rate estimates from the bubble burette method is greater than from electronic flow rate meters. The EFRMs give statistically significant different estimates of the flow rate. However, the magnitude of the difference is within the error range stated by the manufacturers, and included in the overall sampling and analytical error. The error in flow rate estimates points out the need to include confidence intervals in interpreting and reporting results.

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