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Evaluation of Pump Pulsation in Respirable Size-Selective Sampling: Part III. Investigation of European Standard Methods

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ABSTRACT

Lee et al. (Evaluation of pump pulsation in respirable size-selective sampling: part I. Pulsation measurements. *Ann Occup Hyg* 2014a;58:60–73) introduced an approach to measure pump pulsation (PP) using a real-world sampling train, while the European Standards (EN) (EN 1232-1997 and EN 12919-1999) suggest measuring PP using a resistor in place of the sampler. The goal of this study is to characterize PP according to both EN methods and to determine the relationship of PP between the published method (Lee et al., 2014a) and the EN methods. Additional test parameters were investigated to determine whether the test conditions suggested by the EN methods were appropriate for measuring pulsations. Experiments were conducted using a factorial combination of personal sampling pumps (six medium- and two high-volumetric flow rate pumps), back pressures (six medium- and seven high-flow rate pumps), resistors (two types), tubing lengths between a pump and resistor (60 and 90 cm), and different flow rates (2 and 2.5 l min^{-1} for the medium- and 4.4, 10, and 11.2 l min^{-1} for the high-flow rate pumps). The selection of sampling pumps and the ranges of back pressure were based on measurements obtained in the previous study (Lee et al., 2014a). Among six medium-flow rate pumps, only the Gilian5000 and the Apex IS conformed to the 10% criterion specified in EN 1232-1997. Although the AirChek XR5000 exceeded the 10% limit, the average PP (10.9%) was close to the criterion. One high-flow rate pump, the Legacy (PP = 8.1%), conformed to the 10% criterion in EN 12919-1999, while the Elite12 did not (PP = 18.3%). Conducting supplemental tests with additional test parameters beyond those used in the two subject EN standards did not strengthen the characterization of PPs. For the selected test conditions, a linear regression model [$PP_{EN} = 0.014 + 0.375 \times PP_{NIOSH}$ (adjusted $R^2 = 0.871$)] was developed to determine the PP relationship between the published method (Lee et al., 2014a) and the EN methods. The 25% PP criterion recommended by Lee et al. (2014a), average value derived from repetitive measurements, corresponds to 11% PP_{EN}. The 10% pass/fail criterion in the EN Standards is not based on extensive laboratory evaluation and would unreasonably exclude at least one pump (i.e. AirChek XR5000 in this study) and, therefore, the more accurate criterion of average 11% from repetitive measurements should be substituted. This study suggests that users can measure PP using either a real-world sampling train or a resistor setup and obtain equivalent findings by applying the model herein derived. The findings of this study will be delivered to the consensus committees to be considered when those standards, including the EN 1232-1997, EN 12919-1999, and ISO 13137-2013, are revised.

KEYWORDS: EN 1232-1997; EN 12919-1999; ISO 13137-2013; personal sampling pumps; pump fluctuation; pump pulsation; respirable particle sampling

INTRODUCTION

Personal sampling pumps have been used for >50 years to collect aerosol particles in order to assess personal exposure to airborne hazards (Sherwood and Greenhalgh, 1960; Sherwood, 1997). These pumps attempt to maintain a constant, known airflow during sampling, otherwise, collection efficiency will be unknown, and exposure indeterminate. Despite integrating pulsation dampeners within pumps, pump mechanics, such as the reciprocating motion of a piston stroke, may nevertheless modulate the airflow in the sampling train by introducing periodic pulsations into the flow, i.e. pump pulsations (PPs) synchronous with the speed of the motor in the pump. Bartley et al. (1984) and Berry (1991) introduced methods to measure PPs and reported the associated changes in collection efficiency due to pulsations. Bartley et al. found that introducing pulses having amplitude of 1.11 l min^{-1} at a frequency of 34 Hz, to an otherwise pulse-free flow while collecting particles with aerodynamic equivalent diameters between 2 and 5.5 μm, caused collection efficiency to drop by >10%. Subsequently, when a few sampling pumps were tested at 5.5 μm aerodynamic diameter without a damper between a pump and a SIMPEDS cyclone, Berry reported >10% shift of the penetration efficiency (negative) compared to efficiency of the pulse-free flow.

The European Standard EN 1232-1997 (Workplace atmospheres—Pumps for personal sampling of chemical agents—Requirements and test methods) includes a method for measuring PPs and recommends that the amplitude of pulsations be <10% of the mean flow for battery-powered medium-volumetric flow rate pumps (CEN, 1997). The standard calls for placing a mass flow meter, a hot-wire anemometer, an adjustable resistor, a differential pressure gauge, and the pump under test sequentially downstream from the air intake and connected with specified lengths of 6-mm inner diameter rigid tubing. With the pump running at 2.0 l min^{-1}, the resistor is adjusted to create 0.75 kPa pressure drop to simulate particle loading of the filter element. PP data are then acquired from the hot-wire anemometer for evaluation. The EN 12919-1999 (Workplace atmospheres—Pump for the sampling of chemical agents with a volume flow rate over 5 l min^{-1}—Requirements and test methods) details similar setups for high-volumetric flow battery-powered pumps that generate airflows >5 l min^{-1}, except that the mean airflows and associated back pressures are different (CEN, 1999). The same 10% pulsation requirement was adopted for the EN 12919-1999. The International Organization for Standardization Technical Committee 146 (air quality)/Subcommittee 2 (workplace atmosphere)/Working Group 9 (pump performance) (ISO TC 146/SC 2/WG 9) was working on a standard recommending requirements and test methods for personal sampling pumps [Since the inception of this study, ISO TC 146/SC 2/WG 9 finished the project recommending requirements and test methods for sampling pumps and published a standard, ISO 13137-2013 (Workplace atmospheres—Pumps for personal sampling of chemical and biological agents—Requirements and test methods)]. The ISO TC 146/SC 2/WG 9 used both EN methods as a preparatory document and has adopted the same 10% pulsation requirement and similar setup for PP measurement as both EN methods. However, both EN standards and the ISO standard have included a 10% pulsation criterion without validated technical justification.

The National Institute for Occupational Safety and Health (NIOSH) recently evaluated several pumps to characterize PPs (Lee et al., 2014a) and to determine a limit for pulsation that will not cause a collection efficiency shift of respirable particles (Lee et al., 2014b). The test setup used by NIOSH is arguably more representative of real-world performance; Lee et al. (2014a) measured PPs at the inlets of several commercially available cyclones fitted with filters preloaded with particulates to create the appropriate back pressure. Lee et al. (2014b) suggested that maintaining PP amplitude <25% of the mean flow should provide acceptable performance for the respirable particle collection.

Since Lee et al. (2014a) introduced a different approach to measure PP compared to the method in the EN standards, the goal of this study is to characterize PPs according to both EN methods (EN 1232-1997 and EN 12919-1999) and to determine the relationship of PP between the EN methods and the published method of Lee et al. (2014a). Additional test parameters were also investigated to determine whether the test conditions suggested by the EN methods were appropriate for measuring pulsations.

METHODS

Experimental setup

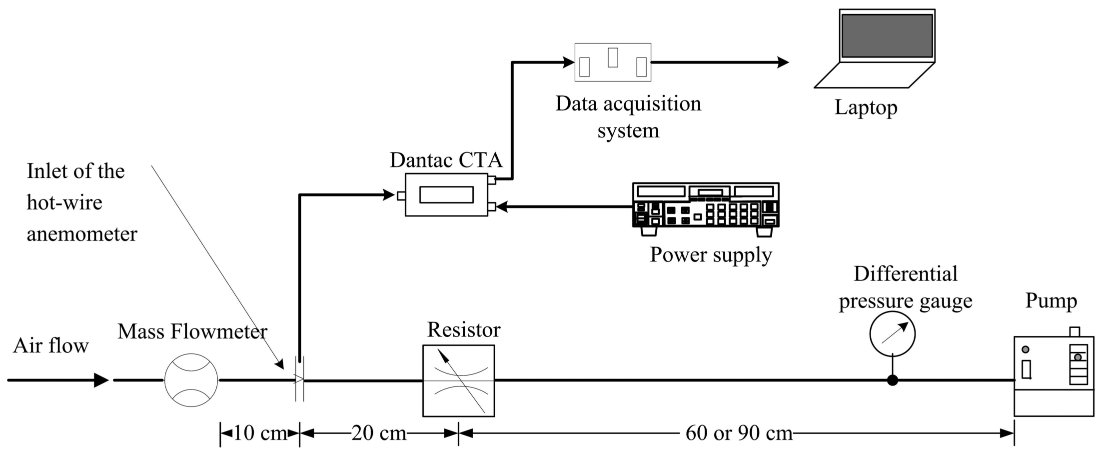
Lee et al. (2014a) measured PPs from a factorial combination of 13 personal sampling pumps (11 medium- and 2 high-volumetric flow rate pumps) and 7 cyclones. Six of these 11 medium-flow rate pumps and both high-flow rate pumps were selected for use in this study. The medium-flow rate pumps selected included those that generated the smallest, largest, and midrange magnitude pulses, but both high-flow pumps were used. Table 1 presents the matrix of test parameters.

Figure 1 shows the experimental setup used to measure PPs according to both EN methods. Both EN methods call for a 60 cm length of rigid tube to connect the pump to the resistor and a 20 cm length of rigid tube to connect the hot-wire anemometer probe to the resistor. Because the distance between the probe and the optional mass flow meter was not specified by either EN method, we chose 10 cm to ensure a short distance. For the medium-volumetric flow rate pumps, the EN 1232-1997 method specified PP measurement upstream of the resistor at the flow rate of 2.0 l min^{-1} with a pressure drop of 0.75 kPa. For the high-volumetric flow rate pumps, the EN 12919-1999 method required that pulsations be measured at a flow rate of the 'mean value of nominal flow rate range' with a pressure drop of the 'lower limit of the nominal range of back pressure for this flow rate'. In the present study, we selected 4.4 l min^{-1} for the flow rate the full range

Table 1. Test parameters for pulsation measurements

Test parameters	Medium-volumetric flow rate pumps[a] (PP %)[b]	High-volumetric flow rate pumps[c] (PP %)[b]
Pump selection	Apex IS (4.4%)	Legacy (14.7%)
	Gilian5000 (12.0%)	Elite12 (41.0%)
	AirChekXR5000 (24.4%)	
	GilAir5 (31.0%)	
	Elite5 (56.2%)	
	Basic5 (69.4%)	
Resistor	NPTF needle valve and screwed-bonnet needle valve	
Back pressure (kPa)	0.75[d], 1.0, 1.25, 1.5, 2.5, and 3.0	1.5, 2.0[e], 2.25, 2.5, 2.75, 3.0, and 3.3
Flow rate (l min^{-1})	2[d] and 2.5	4.4[e], 10, and 11.2
Tubing length (cm)[f]	60[d] and 90	60[e] and 90

[a]Battery-powered personal sampling pumps whose nominal flow rate is up to 5.0 or 6.0 l min^{-1}.
[b]Average PP (%) (Table 4, Lee et al., 2014a).
[c]Battery-powered personal sampling pumps whose nominal flow rate over 5.0 l min^{-1}.
[d]Recommended test condition by the EN 1232-1997 standard.
[e]Since EN 12919-1999 does not provide specific test conditions, we selected 4.4 l min^{-1} with 2.0 kPa based on the measurements reported by Lee et al. (2014a).
[f]Distance between a pump and resistor.



1 Experimental setup to measure PPs.

of high-flow rate pumps and the recommended flow rates for various cyclones by manufacturers. A pressure drop of 2.0 kPa was selected based on measurements performed by Lee et al. (2014a).

Prior to collecting pulsation measurements, a hot-wire anemometer probe (Model Type 55P11; Dantec Dynamics A/s, Skovlunde, Denmark) was calibrated as described by Lee et al. (2014a), but with 20 nominal flow rates instead of nine nominal flow rates. The 20 nominal flow rates were 0.304, 0.492, 1.05, 1.51, 1.72, 1.99, 2.20, 2.75, 3.50, 4.20, 4.39, 6.00, 7.49, 10.0, 11.2, 12.9, 15.0, 17.5, and 20.1 l min^{-1}. Based on the calibration curve, a cubic polynomial equation using SigmaPlot® (Systat Software, Inc., San Jose, CA, USA) was developed and then programmed to the data acquisition system (NI-DAQ 9205 in slot 8 of NI cDAQ-9178, National Instruments Corporation, Austin, TX, USA) to transform the voltage readings (i.e. a total of 25 000 readings collected every 40 µs) into the corresponding flow rates.

As shown in Fig. 1, air was drawn through a mass flow meter positioned at 10 cm upstream of the calibrated probe. The TSI mass flow meter (Model 4143, TSI, Inc., Shoreview, MN, USA) was used to adjust the desired nominal flow rate within 5%. The pressure drop was measured with one of three MK III handheld digital manometers (Models 475-00-FM, 475-0-FM, and 475-1-FM, Dwyer Instruments, Inc., Michigan, IN, USA), depending on the required pressure drop. After adjusting the nominal flow rate and pressure drop, the differential pressure gauge was removed while taking the pulsation measurements, as required by both EN methods. The mass flow meter is also to be removed during these measurements according to both EN methods. However, preliminary study showed that keeping the mass air flow meter in the setup had no effect on PPs. Thus, it was retained to ensure the desired flow rate within 5% during the experiments.

Pulsation measurements at other test conditions were performed to determine if the test conditions suggested by the EN methods were appropriate for measuring pulsations. Below are the justifications for additional parameters (Table 1):

- Resistor type—Two different resistors, Easy Read® NPTF flow control valve (Model EF 20B, Deltrol Fluid Products, Inc., Bellwood, IL, USA) and screwed-bonnet needle valve (Model B-1RS6, Swagelok, Inc., Cleveland, OH, USA), were chosen because no specific resistor type was defined in either EN method. The structure of each valve is slightly different. The NPTF flow control valve has a straight flow pattern in one direction, whereas the screwed-bonnet needle valve has a straight flow pattern in a two-way direction.
- Tubing length—Lee et al. (2014a) obtained pulsation measurements based on various tubing lengths and reported that a tubing length up to ~100 cm had no effect on the pulsation measurements, while a tubing length of 183 cm reduced the pulsation measurements by ~10%. In the present

study, we added a 90-cm tubing length in accordance with US 30 Code of Federal Regulations Part 74.3(5) (1974) for Coal Mine Dust Personal Sampler Units. The tubing length 183 cm was not included because it is too long for personal sample collection. For consistency, the same aluminum rigid tubing material employed by Lee et al. (2014a) was used.

- Flow rates—Lee et al. (2014a) measured PPs at various flow rates, from 1.7 to 2.75 l min^{-1} for the medium-flow rate pumps and 4.4, 10, and 11.2 l min^{-1} for the high-flow rate pumps. Although Lee et al. (2014a) reported that pulsation magnitudes depended on pump model alone and were not affected by flow rates for the tested conditions, one additional flow rate (2.5 l min^{-1}) for the medium-flow rate pumps and two more (10 and 11.2 l min^{-1}) for the high-flow rate pumps were added to confirm those findings.
- Back pressure—In addition to the test condition described in the EN 1232-1997 and EN 12919-1999, five back pressures for the medium-flow rate pump and six for the high-flow rate pump were included to determine pulsations due to different pressure drops. The ranges of back pressures were selected based on the pressure drop measurements by Lee et al. (2014a).

For each test condition, two pumps per pump model were selected and three replicates of each condition were performed. The same pump model units used in the previous study (Lee et al., 2014a) were used in the present study to minimize the variation of PPs within pump model and strengthen the comparison of data. A total number of runs were 1728 runs for the medium-flow rate pumps (6 pump models × 2 pumps/model × 2 resistors × 6 back pressures × 2 flow rates × 2 tubing lengths × 3 replicates = 1728) and 1008 runs for the high-flow rate pumps (2 pump models × 2 pumps/model × 2 resistors × 7 back pressures × 3 flow rates × 2 tubing lengths × 3 replicates = 1008).

Data analysis

Once the flow rates in a text file were imported into an Excel format (Microsoft, Inc., Redmond, WA, USA), PP was calculated using the following equation (CEN, 1997):

$$\mathrm{PP} = \frac{\sqrt{\frac{1}{T}\int_0^T [f(t) - \bar{f}]^2 \, \mathrm{d}t}}{\bar{f}} \qquad (1)$$

where $f(t)$ = volumetric flow rate with respect to time (l min^{-1}), $\bar{f}$ = mean volumetric flow rate over time T (l min^{-1}), t = time (s), and T = time period of pulsation (s).

Firstly, PPs were characterized according to both EN methods from test conditions of 2 l min^{-1} with 0.75 kPa resistance and 4.4 l min^{-1} with 2.0 kPa for the medium- and high-flow rate pumps, respectively. Test conditions of a 60-cm tubing length and both resistors were included for PPs' characterization (Table 1). Secondly, PPs were compared from all test conditions to determine the appropriate factorial combination of pump model/resistor/tubing length/flow rate/back pressure. PP data were analyzed using SAS/STAT software (Version 9.3) for Windows. Replicate measures that were collected for each independent pump and variable combination were averaged prior to the analysis. A five-way factorial analysis of variance was performed using Proc Mixed with fourth and fifth degree interactions removed. Significant interactions were analyzed using the 'slice' option. All differences were considered significant at $P < 0.05$.

Lastly, to determine the relationship of PP between the EN methods and the published method by Lee et al. (2014a), PPs obtained from all factorial combinations of 2.0 l min^{-1} flow rate/0.75 kPa resistance/60- and 90-cm tubing lengths/two resistors for the medium-flow rate pumps were analyzed. For the high-flow rate pumps, PP measurements from conditions of 4.4 l min^{-1} flow rate/2.0 kPa resistance/60- and 90-cm tubing lengths/two resistors were analyzed. For this comparison, both tubing lengths and resistors were included because no differences of PPs between tubing lengths and between resistors were observed. Comparisons between pump types and the published method and the EN method were further analyzed using two-way analysis of variance (Method by Pump type) at the restricted levels of flow and back pressure as described above. In the present study, the PPs obtained at various back pressures showed statistically significant differences for the medium-flow rate pumps. Thus, an empirical equation as a function of back pressure (independent) and PP_{EN} (dependent) was developed for each pump model using SigmaPlot. For this process, PP measurements were analyzed under all test conditions, except for 2.5 l min^{-1} for the medium-flow rate pumps and 10 and 11.2 l min^{-1} for the high-flow rate pumps. From each empirical equation, the PP_{EN} corresponding to the back pressure drop measured by Lee et al. (2014a) was obtained. Then the relationship between the PP_{EN} and PP_{NIOSH} was determined by developing empirical models.

RESULTS

Characterization of pulsation according to the EN methods

Table 2 lists the summary of PPs measured according to the EN 1232-1997 and EN 12919-1999 methods. Overall, two-thirds of the combinations (48 out of 72 runs) generated pulsations >10% of the mean flow, exceeding the limit specified in the EN 1232-1997 (CEN, 1997). Only the Apex IS and the Gilian5000 conformed to this 10% limit. Note that although the AirChek XR5000 (PP = 10.9%) exceeded the limit, the average PP was close to the 10% criterion. One high-flow pump, the Legacy (PP = 8.1%), conformed to the 10% limit in EN 12919-1999, while the Elite12 did not (PP = 18.3%). The PPs of the Elite12 were approximately twice the magnitude of the Legacy pump. The coefficients of variation (CVs) for the high-flow rate pumps were lower than the CVs for the medium-flow rate pumps.

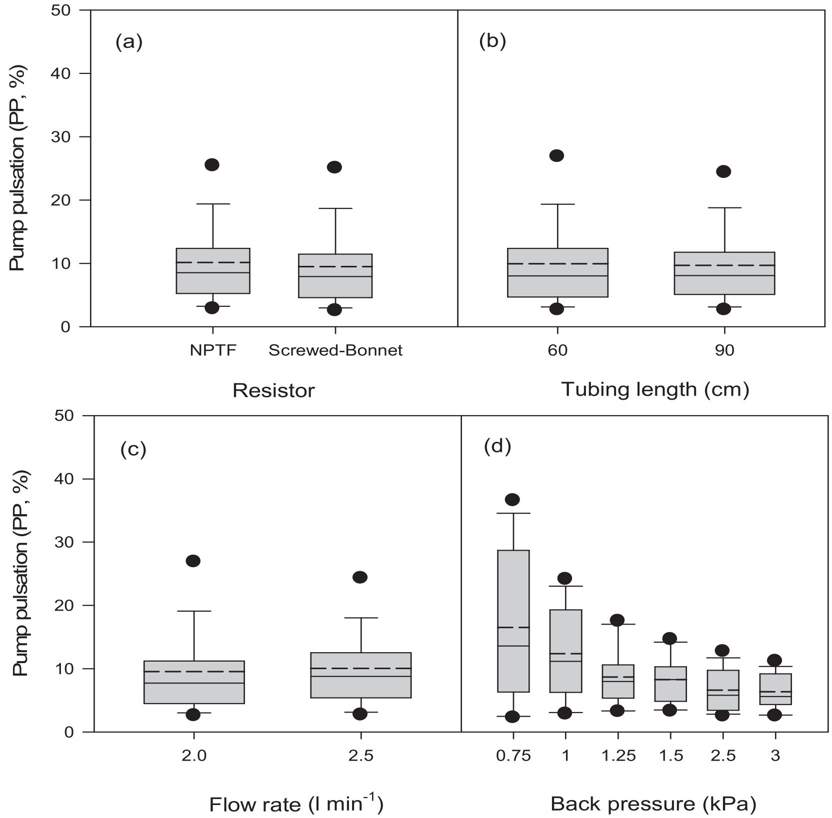
Test conditions according to the EN methods

Figure 2 shows PPs with different test conditions for the medium-flow rate pumps. The change in the PPs between the resistor type (Fig. 2a), the tubing length (Fig. 2b), and the flow rate (Fig. 2c) showed no visual differences. The difference of median PPs for each comparison was <1.5%. However, the statistical tests for those comparisons revealed significant differences (all *P*-values < 0.05) due to such small standard deviations. These parameters had no effect on PP since the differences in both least square means for each comparison were small (<0.006) and the differences in PPs were negligible. On the other hand, the PPs generated under different back pressures displayed (Fig. 2d) noticeable differences and also resulted in statistically significant differences (*P*-value < 0.0001). Figure 3 provides detailed information of PPs under various back pressures for each pump model. Overall, the Apex IS and Gilian5000 showed almost flat patterns, while other pump models, except for the Basic5, showed a gradual decrease of PPs as back pressure increased. The PP generated by the Basic5 was dramatically decreased at 1.25 kPa and increased at 1.5 kPa, i.e. it had larger variation of PPs than other pump models.

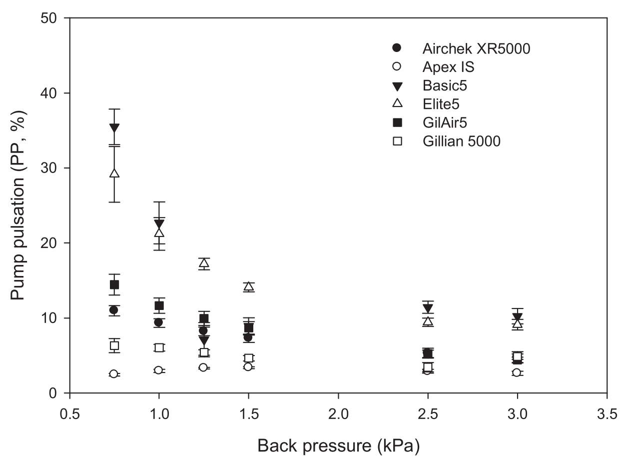
Table 2. Summary of PPs measured according to the EN methods

	Test condition	Pump model	Pump pulsation (%)	
			Mean (CV)	Range
Medium-flow rate pumps	2 l min^{-1} with 0.75 kPa resistance and 60-cm tubing length[a]	Apex IS	2.5 (7.5)	2.3–2.7
		Gilian5000	6.0 (14.8)	5.1–7.1
		AirChek XR5000	10.9 (6.7)	10.1–11.7
		GilAir5	14.8 (6.2)	13.7–15.7
		Elite5	30.6 (14.0)	26.8–34.7
		Basic5	37.8 (7.4)	33.2–39.0
High-flow rate pumps	4.4 l min^{-1} with 2.0 kPa and 60-cm tubing length[b]	Legacy	8.1 (5.9)	7.7–8.7
		Elite12	18.3 (1.5)	18.0–18.6

[a]Recommended test condition by the EN 1232-1997 standard.
[b]Since EN 12919-1999 does not recommend specific test condition, we selected 4.4 l min^{-1} with 2.0 kPa based on the measurements by Lee et al. (2014a).



2 PP obtained from different (a) resistors, (b) tubing lengths, (c) flow rates, and (d) back pressures for the medium-flow rate pumps. Note that each box plot represents selected quartiles of pulsation distributions, including the mean (dashed line), median (50th percentile, solid line), 25th and 75th percentiles, 10th and 90th percentiles (error bars), and 5th and 95th percentiles (solid dots). Included all test conditions except for the interest factor.



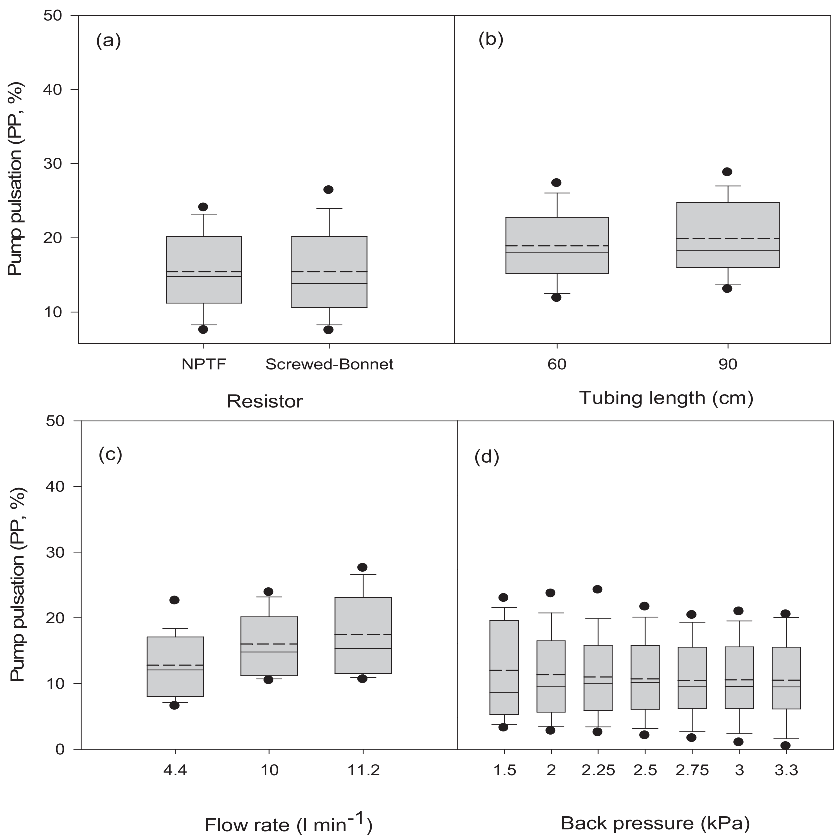
3 PPs and one standard deviation at various back pressures for the medium-flow rate pumps.

Figure 4 illustrates PPs obtained from various test conditions for the high-flow rate pumps. No statistical difference was observed from the comparison of PPs due to different resistor types (P-value = 0.9489). Unlike the medium-flow rate pumps, the PPs at various back pressures showed a flat pattern, indicating no difference of PPs due to different pressure resistances. Although the PP measurements due to other parameters including tubing length, flow rate, and back pressures resulted in statistically significant differences, it would be difficult to distinguish effects of PP due to those factors because of small changes of both least square means (<5%).

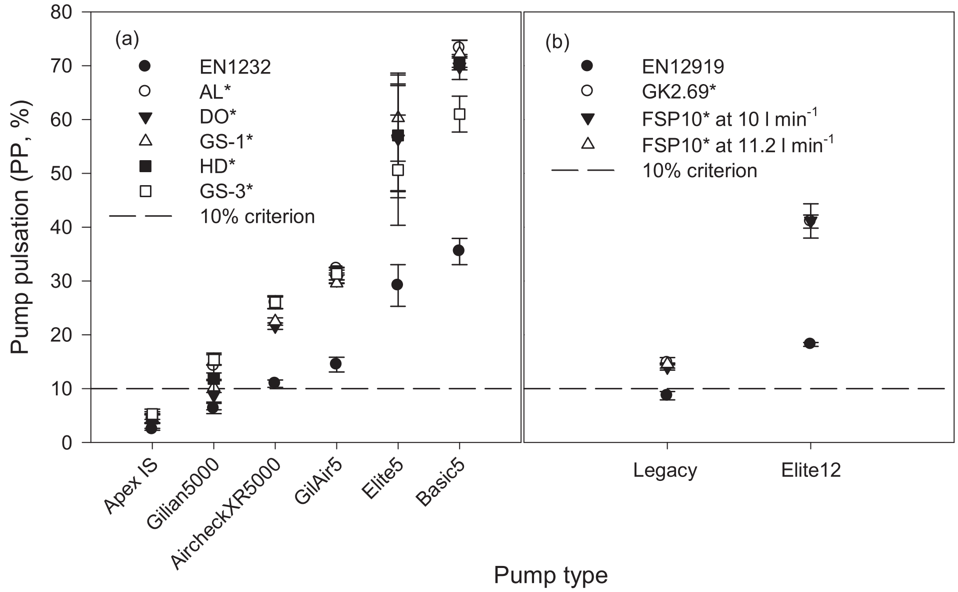
Comparison of pulsations between the published method and EN methods

Figure 5 compares PPs measured by the published method of Lee et al. (2014a) (called PP_{NIOSH}) and laid out in Table 4 of that publication, and in the current work by EN methods (called PP_{EN}). The magnitudes of PP_{NIOSH} were considerably higher than the magnitudes of PP_{EN} for both the medium- and high-flow pumps. The average ratio of PP_{NIOSH} and PP_{EN} ranged from 2.0 to 2.3 for the medium-flow rate pumps and from 1.5 to 2.2 for the high-flow rate pumps. The statistical comparison showed significant differences between PP_{NIOSH} and PP_{EN} for the medium- and high-flow rate pumps (all P-values < 0.0001), except for the Apex IS (P-value = 0.1419).

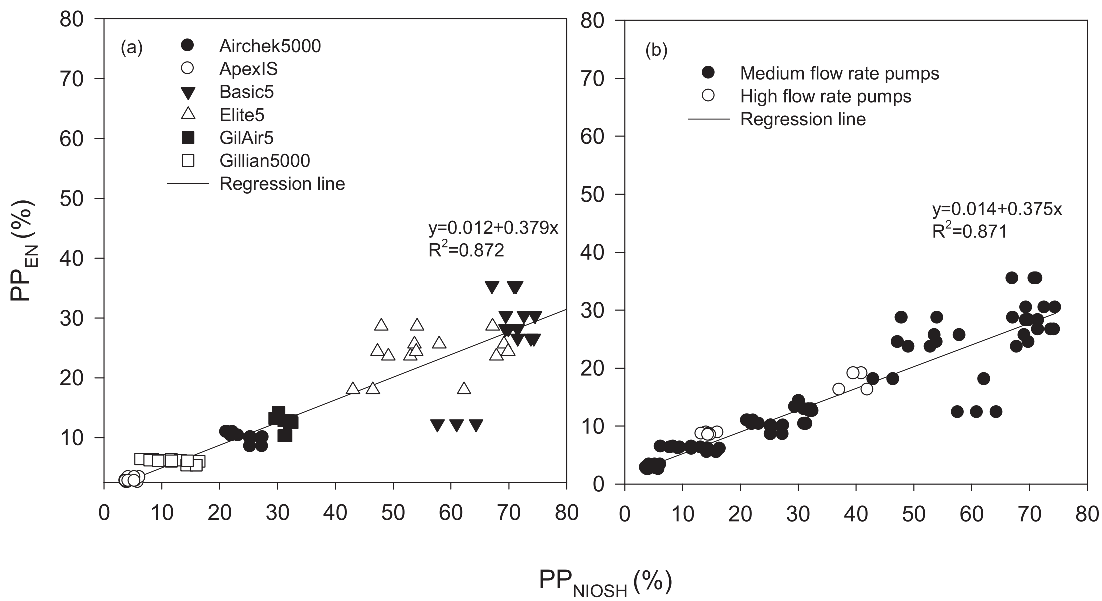
Figure 6a shows the relationship of PP_{NIOSH} and PP_{EN} for the medium-flow rate pumps only. The value PP_{EN} was obtained from an empirical equation [as a function of back pressure (independent) and PP measured according to the EN method (dependent)]



4 PP obtained from different (a) resistors, (b) tubing lengths, (c) flow rates, and (d) back pressures for the high-flow rate pumps. Note that each box plot represents selected quartiles of pulsation distributions, including the mean (dashed line), median (50th percentile, solid line), 25th and 75th percentiles, 10th and 90th percentiles (error bars), and 5th and 95th percentiles (solid dots).



5 Comparison of PPs between the published (Lee et al., 2014a) and EN methods: (a) medium-flow rate pumps and (b) high-flow rate pumps. *The magnitudes of PPs were adopted from Table 4 in Lee et al. (2014a).



6 The relationship of PP between the published (Lee et al., 2014a) and EN methods: (a) medium-flow rate pumps only and (b) medium- and high-flow pumps. Note that the PP_{EN} represents the corresponding PP based on the back pressure measurements at different flow rates by the published method (Lee et al., 2014a).

for each sampling pump. The PP_{EN} then was compared with the corresponding PP_{NIOSH}. A linear regression model was developed as follows:

$$PP_{EN} = 0.012 + 0.379 \times PP_{NIOSH} \left(\text{adjusted } R^2 = 0.872\right) \quad (2)$$

Figure 6b represents the combined results of both medium- and high-flow rate pumps, and the predicted equation for the combined data is as follows:

$$PP_{EN} = 0.014 + 0.375 \times PP_{NIOSH} \left(\text{adjusted } R^2 = 0.871\right) \quad (3)$$

The slope of the regression model (0.375) was the same as for that of equation (2) (0.379), indicating a consistent relationship regardless of pump type. The adjusted R^2 is also nearly the same for both equations (2) and (3).

DISCUSSIONS

Characterization of pulsation according to the EN methods

Lee et al. (2014a) reported that the PPs decreased in the order of Basic5 (PP = 69.4%) > Elite5 (PP = 56.2%) > GilAir5 (PP = 31.0%) > Airchek XR5000 (PP = 24.4%) > Gilian5000 (PP = 12.0%) > Apex IS (PP = 4.4%). This order is conserved in the present study (Table 2), although the PP magnitudes are different. Only the Apex IS and Gilian5000 met the EN 10% PP criterion in this study. The high-flow rate pumps also produced the same order of PP magnitudes (i.e. Elite12 > Legacy) as the findings by Lee et al. (2014a). The present study also confirmed that the PPs were mostly dependent on pump model with an additional small contribution from back pressure (see below).

Test conditions according to the EN methods

In addition to the test conditions in each EN method, the present study investigated the effect on PPs of various factors including resistor type, tubing length, flow rate, and back pressure. Below are the study findings and discussion for each factor:

- Resistor type—Although the flow pattern of each resistor was different (i.e. a flow pattern in one-way for the NPTF flow control valve and two-way for the screwed-bonnet valve), the pulsation magnitudes due to different resistors were not different for both medium- and high-flow rate pumps (Figs 2 and 4). The median PPs for the NPTF flow control valve and the screwed-bonnet needle valve were 8.6 and 7.9% for the medium-flow rate pumps and 14.8 and 13.7% for the high-flow rate pumps. Only straight flow patterns in either one-way or two-way orientation were used in the present study. Other structures of flow patterns, such as an angle pattern, have not been tested. Since the selection of resistor was not specified in both EN standards at the time of this study, the findings of this study suggest that any resistor having a straight flow pattern can be added to the revision of current EN and ISO standards.
- Tubing length—Previous studies by Lee et al. (2014a) and Berry (1991) observed no effect on pulsation for tubing length up to 100 cm. The current study using 60- and 90-cm tubing lengths resulted in the same findings for both medium- and high-flow rate pumps. The differences of median PPs between 60- and 90-cm tubing lengths were only 0.1% PP for the medium-flow rate pumps and 0.2% PP for the high-flow rate pumps. Thus, it would not be necessary to add additional tubing length for testing pump performance in terms of pulsation.
- Flow rate—For both medium- and high-flow rate pumps, the PPs were not affected by different flow rates (the difference in both least square means for each comparison was <5%). The findings of the present study support those by Lee et al. (2014a), demonstrating no effect on PP due to flow rates.
- Back pressure—For the medium-flow rate pumps, overall, PPs gradually decreased as back pressure increased (Fig. 2d), although some pumps (e.g. Apex IS and Gilian5000) showed almost flat patterns (Fig. 3). Lee et al. (2014a) mentioned that the PPs at various resistances showed no patterns for each pump model. However, that study was limited to the more limited range of pressure resistance between 0.76 and 1.07 kPa. When the Basic5 was tested at 1.25 kPa [i.e. beyond the range of pressure resistance tested by Lee et al. (2014a)], PP dramatically decreased, but then increased at 1.5 kPa (Fig. 3). Thus, this resistance effect on pulsation should not be ignored. However, adding additional back pressure(s) to the current test condition (i.e. 0.75 kPa) might not be necessary because of the highest PP observed at 0.75 kPa. One might consider additional back pressure <0.75 kPa with the assumption that the

smaller the back pressure, the larger the PP. This is also not necessary because the 0.76 kPa was the lowest back pressure measured at the inlet of a respirable cyclone at various flow rates [Table 3 in Lee et al. (2014a)]. For the high-flow rate pumps, the PPs at different back pressures were similar, generating almost flat lines shown in Fig. 4. This result indicates that it is not necessary to add additional back pressure to measure PP.

Overall, for the medium-flow rate pumps, the current test condition (2.0 l min^{-1} with 0.75 kPa) recommended by the EN 1232-1997 method was satisfactory to test pump performance in terms of pulsation. For the test condition of high-flow rate pumps, the EN 12919-1999 recommended a mean value of nominal flow rate range with the flow resistance to the lower limit of the nominal range of back pressure for this flow rate (Section 6.5.2 in EN 12919-1999). This statement is ambiguous and may cause confusion to the users. It would be clearer if a specific test condition was stipulated. Based on the findings in the present study, we selected a test condition of 2.0 kPa resistance with 4.4 l min^{-1} as this is the flow-rate we recommend for a particular commercially available cyclone, but as the Standard refers to pumps "*with a volume flow rate of over* 5 l min^{-1}", it might be more appropriate to select a higher flow-rate for the Standard test. In the absence of a flow-rate effect on PP, any flow-rate that meets committee consensus could be used.

Comparison of pulsations between the published method and EN methods

Overall, the PPs measured using a flow resistor (i.e. according to the EN 1232-1997 and EN 12919-1999) were consistently lower than those measured using a real-world sampling train [i.e. according to the method suggested by Lee et al. (2014a)]. Perhaps the different mechanical nature of the in-line resistor compared to the respirable cycloes introduced destructive interferences reducing the resonance effects discussed by Bartley et al. (1984). As described in the Results section, two predicted models—one with medium-flow rate pumps only and the other one with both the medium- and high-flow rate pumps—did not appear to be different (Fig. 6). For example, 70% PP of the Basic5 by the published method (Lee et al., 2014a) would predict a corresponding 28% PP according to EN method for both models.

Both EN and ISO methods recommend a 10% criterion as an acceptable pulsation without justification. Lee et al. (2014a,b) studied sampling efficiency shift due to PP in respirable size-selective sampling as a subsequent study of pulsation measurements at the inlet of a cyclone connected to a pump. Those findings suggest that applying a 25% PP limit (i.e. an average value derived from repetitive tests) to measurements made at the inlet of the cyclone is appropriate in that no significant shift in sampling efficiency was observed compared to collection using a pulse-free flow. A PP_{NIOSH} of average 25% corresponds to a PP_{EN} of average 11% when applying equation (2) or (3). Thus, the findings of this study support the current 10% EN criterion as an acceptable pulsation, but if 11% is used the AirChek XR5000 would also meet the criterion. One limitation is that the developed regression models have only been validated for the range of test conditions used in this study. Caution should be applied when using the regression model with a PP obtained from the test conditions outside the range of those specified in the present study.

CONCLUSIONS

The approach for measuring PPs differs between the method suggested by Lee et al. (i.e. using a real-world sampling train) and EN methods (i.e. using a resistor setup). In order to find the relationship between those methods, extensive experiments were performed using the same personal sampling pumps used in the previous study by Lee et al., as well as including parameters other than the test condition recommended by the EN methods. The findings of this study show that the PPs measured using a real-world sampling train were consistently higher than the PPs obtained according to the EN methods (2–2.3 times higher for the medium-flow rate pumps and 1.5–2.2 times higher for the high-flow rate pumps). The PPs obtained by considering parameters other than the recommended test condition in the EN 1232-1997 method revealed that no additional test conditions were necessary. For the high-flow rate pumps (EN 12919-1999), providing a specific test condition such as 4.4 l min^{-1} with 2.0 kPa resistance instead of a narrative suggestion would be helpful and eliminate confusion by users. The developed regression model indicates that the acceptable 25%

PP criterion recommended by Lee et al. corresponds to 11% PP by the EN methods, indicating that the current 10% criterion (required by the EN methods without justification) is valid, but overcautious in that it unreasonably excludes at least one pump, and so should be modified to read 11%. This study suggests that users can measure PP using either a real-sampling train or a resistor setup and use the developed model reciprocally to obtain a value equivalent to the other test method. The findings of this study will be delivered to the consensus committees to be considered when those standards, including the EN 1232-1997, EN 12919-1999, and ISO 13137-2013, are revised.

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DISCLAIMER

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the Centers for Disease Control and Prevention. Mention of commercial product should not be construed to imply endorsement.

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