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Original Article

Evaluation of a New Workplace Protection Factor–Measuring Method for Filtering Facepiece Respirator

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ABSTRACT

Background: This study aims to assess whether the TSI PortaCount (Model 8020) is a measuring instrument comparable with the flame photometer. This would provide an indication for the suitability of the PortaCount for determining the workplace protection factor for particulate filtering facepiece respirators.

Methods: The PortaCount (with and without the N95-Companion™) was compared with a stationary flame photometer from Moores (Wallisdown) Ltd (Type 1100), which is a measuring instrument used in the procedure for determining the total inward leakage of the particulate filtering facepiece respirator in the European Standard. Penetration levels of sodium chloride aerosol through sample respirators of two brands (A and B) were determined by the two measuring systems under laboratory conditions. For each brand, thirty-six measurements were conducted. The samples were split into groups according to their protection level, conditioning before testing, and aerosol concentration. The relationship between the gauged data from two measuring systems was determined. In addition, the particle size distribution inside the respirator and outside the respirator was documented. Linear regression analysis was used to calculate the association between the PortaCount (with and without the N95-Companion™) and the flame photometer.

Results: A linear relationship was found between the raw data scaled with the PortaCount (without N95-Companion™) and the data detected by the flame photometer ($R^2 = 0.9704$) under all test conditions. The distribution of particle size was found to be the same inside and outside the respirator in almost all cases.

Conclusion: Based on the obtained data, the PortaCount may be applicable for the determination of workplace protection factor.

1. Introduction

Hazardous airborne substances such as aerosols at the workplace may cause diverse occupational diseases; therefore, protective controls are very important for the workers to achieve safe working conditions. The hierarchy of controls follows the so-called "STOP-Principle". This principle can be used to choose protective measures against hazardous substances. As the first step, substitution with a less-dangerous substance or process should be considered. The second step is the possible implementation of technical solutions. Third, organizational solutions may be considered. If all of these solutions do not eliminate or minimize the hazard, personal protective equipment may be necessary. The respiratory protective device is one type of the personal protective equipment that protects a worker from airborne hazards by providing the wearer with clean air.

The performance of respiratory protective devices can be described by the term "protection factor", which has several definitions. The "Nominal Protection Factor (NPF)" represents the level of protection provided by a respirator under standard laboratory test conditions. Corresponding to NPF is the "(total) inward leakage" as used in European Standards, which can be converted into the NPF [1]. The total inward leakage test is a part of requirements in European Standard (EN 149:2001 + A1) if a

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particulate filtering facepiece respirator needs to be approved. The total inward leakage consists of face seal leakage, filter penetration, and exhalation valve leakage, and is measured with a stationary flame photometer [2]. It is tested under laboratory test conditions with a series of test subjects by using defined sodium chloride aerosol. It is presented by a ratio between the aerosol concentration inside the respirator and the aerosol concentration outside the respirator in consideration of breathing frequency [2]. It is reasonable to conclude that NPF cannot indicate a protection level of a respirator achieved under actual working conditions. The main reason for the discrepancy between laboratory testing and the use of the respirators at the workplace is that the simulated exercises in the laboratory do not represent all activities that can occur in the workplace. Furthermore, the respirators are only tested by a small group of test subjects while in the laboratory [1]. The last point to be made here is that sodium chloride aerosols may differ from the aerosols encountered in the workplace. Therefore, the "Assigned Protection Factor (APF)" is applied to indicate the level of protection likely to be achieved in the workplace by 95% of trained respirator users [1]. The realistic level of protection in the workplace is characterized by the "Workplace Protection Factor (WPF)", which should be determined under working conditions by measuring the concentration of a hazardous substance outside and inside the respirator [1]. Therefore, the establishment of APF values should be based on the WPF data [3].

Owing to a lack of standardized test procedures for the measurement of WPF for particulate filtering facepiece respirators in Europe and insufficient WPF data, the APF values are established through a combination of a small number of workplace studies and professional judgment. Consequently, the APF values are different even for the same class of respirator in various European countries [1]. Therefore, it is necessary to carry out more WPF measurements and provide more WPF data for testing if the current APF are appropriate and for determining APF values conclusively.

The traditional sampling method consists of a personal sampling pump and filter cassette and has been used for inside and outside respirators sampling [4–10]. The sampling periods can vary between one and four hours [8]. Laboratory analytical methods are necessary for the determination of the particle masses [3]. This method is widely used in workplace studies and provides high efficiency for sampling in the facepiece [11].

In the past few years, several workplace studies have been conducted using count-based methods, such as direct-reading instruments [12–14]. Compared with the traditional sampling method, a direct-reading instrument can offer an effective measurement procedure and more information on temporary exposures. Furthermore, particle count methods have been recommended for testing respirator filters, in particular, against ultrafine particles [15]. In this study, a direct-reading measuring instrument named "PortaCount 8020" (TSI Inc., Shoreview, MN, USA) is taken into account as a possible instrument for conducting workplace measurements. The PortaCount was chosen because it can determine the particle number concentration inside and outside the respirator. In addition, it is already known for simulated workplace studies [16,17]. The PortaCount 8020 is originally designed for a fit test. This test is used to determine how well a specific respirator fits its user by evaluating the face seal leakage. The PortaCount 8020 has a wide measuring range and, at the same time, is transportable. Those features make it a suitable measuring instrument to be used at the workplace.

The flame photometer is the standard measuring instrument for determining the total inward leakage of the particulate filtering facepiece respirator in Europe [2] and it measures the mass concentration of particles (mass-based method), whereas the PortaCount measures particle number concentration (count-based method). Owing to that, it is needed to verify the appropriateness of the PortaCount and validate it against the flame photometer. Therefore, a comparison study was conducted between the PortaCount and the flame photometer. This verification can provide the basis for conducting the measurements of WPF with PortaCount in actual workplaces.

The purpose of this research is to examine whether a linear relationship between the PortaCount and the flame photometer exists, to establish a method for the measurement of WPF in workplaces.

2. Materials and methods

2.1. Instrument description

All measuring devices used in this study are described in detail below.

2.1.1. Flame photometer

The flame photometer from Moores (Wallisdown) Ltd (Type No. 1100) is a part of the standard test setup for the determination of total inward leakage of particulate filtering facepiece respirators [2] and particle filter penetration [18]. It measures the mass concentration of sodium chloride aerosol by determining the intensity of emitted light radiated from the sodium element. The test aerosol is generated from a sodium chloride solution by an atomizer. The measurement range of the flame photometer is from 0.0001 to 100% of a 13 mg/m^3 sodium chloride aerosol.

2.1.2. PortaCount 8020

The purpose of a fit test is to examine the face seal between a respirator and its user regardless of the penetration caused by its filter material. The PortaCount (Model 8020) from TSI Incorporated is a measuring instrument designed for conducting the fit test. It can measure the number of particles occurring outside the respirator and inside the respirator separately. The respirator fit is then presented by the ratio between the particle number concentration outside the respirator and inside the respirator. This ratio is called a fit factor (see Equation 1) [19].

$$Fit\ Factor = \frac{Outside\ \ concentration}{Inside\ \ concentration} \quad (1)$$

It should be noticed that, for particulate filtering facepiece respirators, particles penetrate in various ways, including face seal leakage and filter material as well as the exhalation valve (if the exhalation valve functions incorrectly), which means, for the fit factor measured with PortaCount alone, all the penetrated particles are counted. The fit factor measured in this way is actually equal to a protection factor because the filter penetration cannot be eliminated.

To eliminate the filter penetration and obtain a correct fit test result for the respirator with low filter efficiency, an accessory of PortaCount named "N95-Companion™" (TSI Inc., Shoreview, MN, USA) can be used for this situation. The N95-Companion™ functions as an aerosol preconditioner for the PortaCount and it can be attached to the PortaCount [20]. The N95-Companion™ contains an electrostatic particle classifier, which selects particles with the particle size range from approximately 0.03 to 0.06 μm and transfers them to the PortaCount for the fit test [20]. Such particles are highly likely to penetrate through the face seal and cannot get through the N95/R95/P95 filter medium, which means that only the face seal leakage is measured.

The principle of the PortaCount is based on a condensation particle counter (CPC). The concentration range of the PortaCount is from 0.01 to 5×10^5 particles/cm^3 with the particle size range from

0.02 μm to greater than 1 μm. The flow rate of the aerosol sampling is 0.7 L/min [19].

In this study, particle concentrations measured by PortaCount and PortaCount with N95-Companion™ can be recorded continuously each second by Software DASYLab (National Instruments, Austin, TX, USA).

2.1.3. Electrical low pressure impactor (ELPI™)

Because the flame photometer and the PortaCount have entirely different measuring principles, it is reasonable to assume that a change of aerosol size distribution due to a filter material could be an influencing variable for comparing the flame photometer and the PortaCount. Therefore, the ELPI™ was applied in this study to determine the size distribution of the challenge aerosol outside the respirator and inside the respirator. This was done to verify if the particle size distribution changes after particles penetrate the respirator. In case of a change, the effect on the results of the measurement could be observed.

The ELPI™ (Dekati Ltd., Tampere, Finland) is a real-time measuring device for determining the particle size distribution. The ELPI™ can measure the particle size distribution in the size range of 0.03 – 10 μm with 12 channels. The flow rate of sampling is 30 L/min [21]. The result of ELPI™ presents the particle number concentration [1/cm^3] in each size range.

2.2. Challenge aerosol

In Europe, a sodium chloride aerosol is required for measuring total inward leakage of filtering facepiece respirators [2] and penetration of filter materials [18]. In this study, the sodium chloride aerosol was generated from a sodium chloride solution using a Collison atomizer (flowrate 13 L/min at 50 psig).

Owing to the different measuring ranges of the flame photometer and the PortaCount, the highest concentration of sodium chloride solution applied for both devices needed to be tested. A fast way of determining the solution concentration is measuring the conductivity of the solution, as the conductivity of the sodium chloride solution is proportional to the concentration of the solution. Because the conductivity of the solution can be affected by the solution temperature, the “inoLab PH/Cond 720” (WTW GmbH, Weilheim, Germany) was used in this study. This device is able to measure the conductivity of a solution while considering the solution's temperature [22].

A solution with a conductivity of 100 μS/cm was determined as the highest concentrated solution to be used in this study. For a solution of that concentration, the amount of particles is approximately 3.5×10^5 particles/cm^3, which is below the upper limit of the PortaCount.

The comparative test in this study was conducted under two concentrations of the sodium chloride solution, one was the high concentration with the conductivity of 100 μS/cm and the other one was the low concentration with the conductivity of 50 μS/cm (approximately 2.3×10^5 particles/cm^3).

2.3. Tested respirators

This study was focused on EN-certified particulate filtering facepiece respirators, which protect users from both solid and liquid aerosols in ambient atmosphere [2]. The whole facepiece of the respirator is a filter material and it may be equipped with an exhalation valve. Compared with an elastomeric respirator, a particulate filtering facepiece respirator is usually disposable [23]. There are three classes of European certified CE-marked particulate filtering facepiece respirators: FFP1, FFP2, and FFP3. The classification is based on the efficiency of the filter material and its tested value of total inward leakage [2]. For FFP1 respirator, the maximum penetration of filter material is 20% and the maximal allowable total inward leakage is 22% [2]. The maximum penetration of filter material of FFP2 respirator is 6% and the total inward leakage should be less than 8% [2], which means that a FFP2 respirator should equate to a N95 respirator used in the United States. The maximum allowable penetration of filter material for FFP3 respirator is only 1% and the total inward leakage should be less than 2% [2].

Fig. 1. Test chamber.

Two major brands of particulate filtering facepiece respirators in the German market were chosen for this study (hereafter referred to as brands A and B). Respirators with protection classes of FFP1, FFP2, and FFP3 from these two brands were included. Brand A respirators were cup-shaped in design, whereas brand B were folded. All chosen respirators were without exhalation valves; therefore, total inward leakage in this study consists only of filter penetration and face seal leakage.

The respirators were compressed in a metallic test chamber with an inner basket (see Figs. 1 and 2). The respirators were adjusted to the basket and sealed by means of a butyl sealant (TEROSTAT). The filled basket was introduced in the test chamber, which densely compressed the basket through three metallic grips.

Considering that the comparability between the flame photometer and the PortaCount should exist regardless of whether a respirator fitted by a user, the respirators were tested under two situations (see Fig. 3). The first situation was the original respirator

Fig. 2. Basket with a respirator.

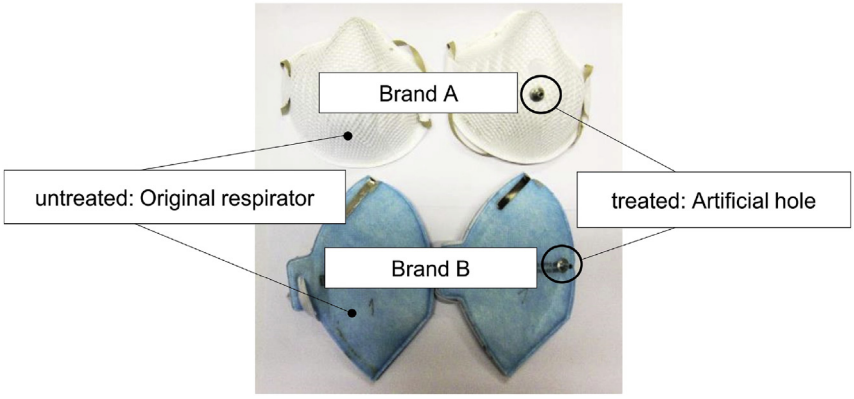


Fig. 3. Treatments of respirators.

(untreated respirator). The total inward leakage of untreated respirator consists only the filter penetration, which simulated a properly fitting respirator. The second situation was the respirator with an artificial hole (treated respirator), the aim of the hole is to simulate the face seal leakage. Therefore, the total inward leakage of treated respirators consists of the face seal leakage and the filter penetration. The artificial hole (Ø 3 mm) was located in the middle line of the tested respirator and it was made with a Probe-Kit provided by TSI Incorporated. This simulation method is similar to the method described by Rengasamy and Eimer [24].

2.4. Comparative test

The experimental setup for comparing the flame photometer and the PortaCount (with and without the N95-Companion™) is shown in Fig. 4.

This experimental setup was based on the nominal test method for determination of particle filter penetration [18]. The challenge aerosol was generated from the atomizer. It was mixed with the dry clean air in the evaporator tube and led into a test chamber with a flow rate of 95 L/min. The tested respirator was installed in the test chamber to determine the concentration of the test aerosol behind the respirator. The test aerosol concentration in front of the respirator was determined directly without the respirator in the test chamber under the same concentration.

In the original standard test setup, the entire challenge aerosol (with a flow rate of 95 L/min) is transferred directly to the flame photometer. The flame photometer takes only a small part of the sample flow for determining the particle concentration; the remaining airflow is normally filtered and then released into the atmosphere. In the current experimental setup, the remaining airflow was not filtered. Hence, this remaining flow was used for a simultaneous measurement with PortaCount, PortaCount with the N95-Companion™ and ELPI™. To avoid overpressure caused by high flow rate, a three-necked flask was applied for recollecting the remaining airflow (see Fig. 4).

As a result of a separate measurement, it was found that there was only a small difference between the particles after the test chamber and in the three-necked flask. The particle concentrations measured by PortaCount varied within 6%. Particle size distributions measured by TSI Scanning Mobility Particle Sizer (SMPS) (Classifier Model 3080, DMA Model 3081, CPC Model 3025) showed a minor shift of small particle sizes (Fig. 5), which indicates a systematic error of the experimental setup. Two main reasons are considered for this minor shift: diffusion losses of small particles in a long tube and temporary or occasional instability of the atomizer. However, the minor shift of particle size should not lead to any perceptible impact on measuring results.

The penetration through the respirator was measured by the flame photometer, PortaCount and PortaCount with N95-Companion™. A complete measurement of the particle penetration consisted of the following single measurements: (1) particle concentration in the test chamber without the respirator; (2) particle concentration in the test chamber with the respirator (C_2); (3) particle concentration in the test chamber without the respirator (control measurement). The particle concentration outside the respirator (C_1) was determined by calculating the average concentration of the measurement (1) and (3). The penetration was calculated using the Equation 2 [18]:

$$P(\%) = \frac{C_2}{C_1} \times 100 \quad (2)$$

The duration of each measurement was 30 sec and every measurement began 3 minutes after the start of the experiment. The single measurement of penetration was repeated three times for one respirator under one concentration of challenge aerosol. For each single repetition, a new respirator was applied. The concentration of the test aerosol from the atomizer remained stable during one penetration measurement; the particle size distributions outside the respirator and inside the respirator were documented during each measurement by the ELPI™.

2.5. Data analysis

The data were presented and analyzed using Microsoft Excel 2016 and IBM SPSS Statistic 23.

2.5.1. Particle size distributions

The arithmetic mean values of the particle number concentration in each particle size range from three repetitions were calculated for particles inside the respirator as well as particles outside the respirator. The objective was to examine whether the shape of the distribution inside the respirator was different from the shape of the distribution outside the respirator.

If the fractional separation efficiencies, for every particle size, of a filtering facepiece respirator are the same, it can be argued that the particle size distribution is the same outside and inside the respirator. Thus, the ratio between the total particle number concentration over the entire size range inside the respirator and outside the respirator was determined for each test. The product of

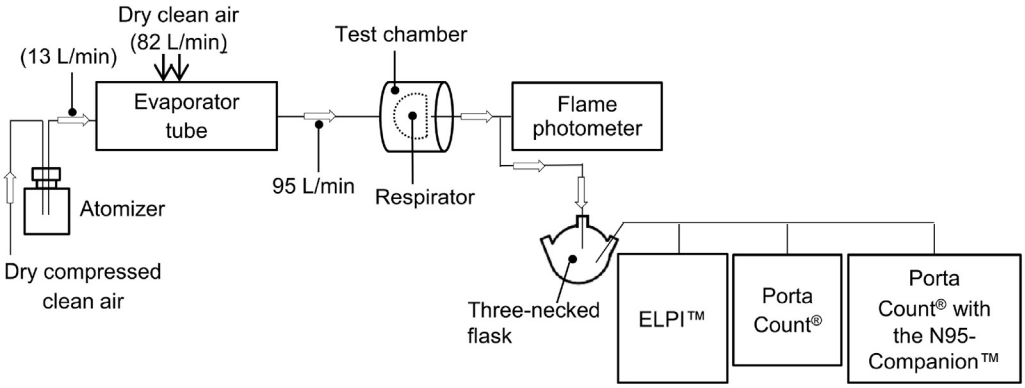


Fig. 4. Experimental setup.

this ratio and observed concentration of each particle size range outside the respirator was the expected concentration of each particle size range inside the respirator. Therefore, Chi-square goodness-of-fit test was used to assess whether the difference of the observed concentration (inside the respirator) and the expected concentration (inside the respirator) were statistically significant. This idea was organized into the following hypotheses:

H0. The observed concentration is the same as the expected concentration in each size range inside the respirator, which means that the concentrations were equally reduced for each size range under the use of the respirator and the shape of particle size distribution inside the respirator is identical to the shape outside the respirator.

H1. The observed concentration is not the same as the expected concentration in each size range inside the respirator, which means that the particle size distribution was changed under the use of the respirator.

One condition of using the Chi-square goodness-of-fit test is that each scenario must have more than five counts [25]; hence, in each size range, there must be at least five particles. The results of ELPI™ showed that behind some respirators (e.g., FFP3 respirator), there were less than five particles in some size range; therefore, these unfitted groups were combined with contiguous groups and analyzed together.

2.5.2. Data from penetration measurements

The arithmetic mean values of three repetitions from the penetration results were calculated. The relationship between the flame photometer and the PortaCount as well as between the flame photometer and the PortaCount with the N95-Companion™ were analyzed by means of regression analysis.

3. Results and Discussion

3.1. Particle size distribution

Examples of the results from the ELPI™ are presented in Figs. 6 and 7 (the complete results are provided as Supplementary material). All the results are the arithmetic mean values of three repetitions. Logarithmic scales on both X-axis and Y-axis are used to provide a clear presentation of results.

Fig. 6 shows the particle size distributions of FFP1 from brand A under both high and low concentrations. The shape of the particle size distribution remains the same whether it is outside the respirator or inside the respirator under both concentrations. On the contrary, changes of particle size distributions are observed by FFP1 from brand B (see Fig. 7), for example, for the untreated respirator under low concentration.

To test the hypotheses about the particle size distribution, the Chi-square foodness-of-fit tests are presented here in the Table 1 and Table 2. The predetermined significance level was 5% ($\alpha = 0.05$).

In most of the sample cases, the shape of the particle size distribution inside the respirator was the same as that outside the respirator, except for four cases.

(1) untreated FFP3 brand A respirator at high concentration;
(2) untreated FFP1 brand B respirator at high concentration;
(3) untreated FFP1 brand B respirator at low concentration;
(4) treated FFP1 brand B respirator at low concentration.

A change in the particle size distribution was observed in one FFP3 respirator. A possible reason is that an FFP3 respirator filter will have very low penetration when untreated. The particle

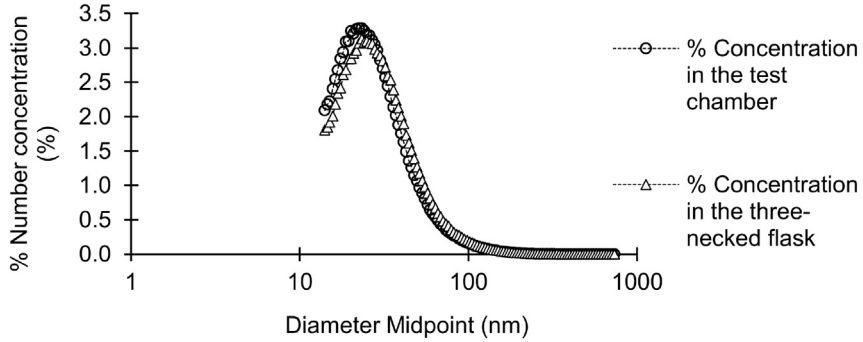
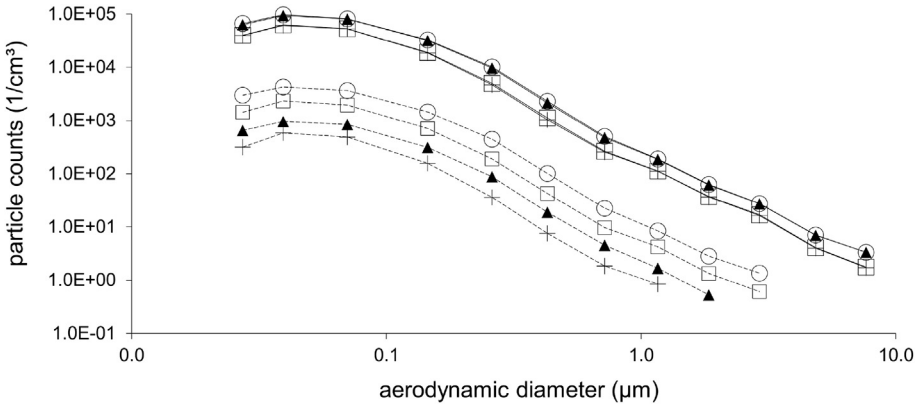


Fig. 5. Particle size distribution after the test chamber and in the three-necked flask.



FFP1 respirator (brand A)		Particle counts	
Treatment	Concentration	Outside the respirator	Inside the respirator
untreated	high	▲	▲
treated	high	○	○
untreated	low	+	+
treated	low	□	□

Fig. 6. Particle size distribution of FFP1 respirator from brand A. FFP, filtering facepiece.

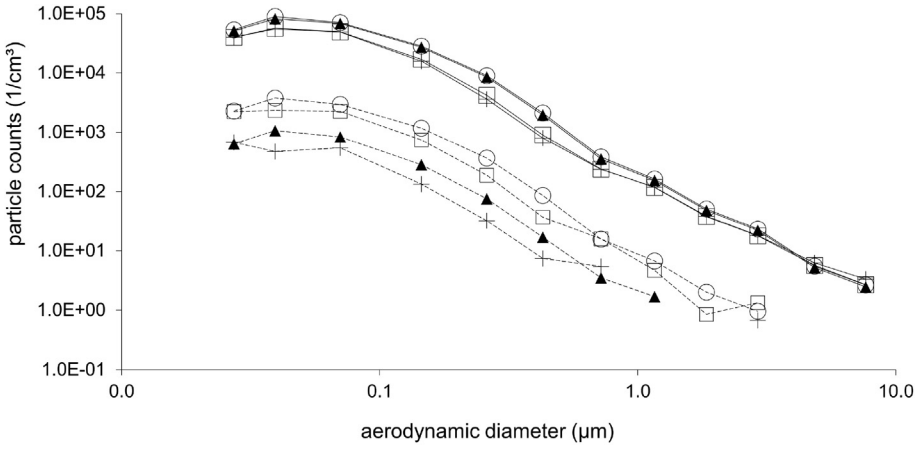
concentration inside the facepiece will be very low, making it difficult for the ELPI™ to measure adequate particles for determining the particle size distribution.

It is observed that FFP1 respirator from brand B also performed a change in the particle size distribution. It could be inferred that this change was due to the existence of the most penetrating particle size of filter material. The penetration levels at the most penetrating particle size can be higher than other particle size [26], which may lead to a change in the size distribution after particles penetrate the respirator.

3.2. Penetration

The arithmetic mean values of penetration results of the flame photometer, the PortaCount and the PortaCount with the N95-Companion™ are shown in Fig. 8 and Fig. 9. The error bars represent the standard error of mean values (n = 3). The results are sorted in ascending order for the penetration results of the flame photometer.

It is noticed that, as the protection level of respirator increases, the particle penetration is not simultaneously reduced. For



FFP1 respirator (brand B)		Particle counts	
Treatment	Concentration	Outside the respirator	Inside the respirator
untreated	high	▲	▲
treated	high	○	○
untreated	low	+	+
treated	low	□	□

Fig. 7. Particle size distribution of FFP1 respirator from brand B. FFP, filtering facepiece.

Table 1
Results of Chi-square test of respirators from brand A

Mask (Treatment)	Sodium chloride solution [μS/cm]	df	Chi-square statistic	Asymptotic significance	Hypothesis
FFP1 (untreated)	100	6	3.021	0.806	H0
FFP1 (treated)	100	7	2.443	0.931	H0
FFP2 (untreated)	100	6	0.603	0.996	H0
FFP2 (treated)	100	7	0.243	1.000	H0
FFP3 (untreated)	100	4	88.920	0.000	H1
FFP3 (treated)	100	7	2.581	0.921	H0
FFP1 (untreated)	50	5	9.211	0.101	H0
FFP1 (treated)	50	7	0.689	0.998	H0
FFP2 (untreated)	50	5	1.812	0.875	H0
FFP2 (treated)	50	7	1.279	0.989	H0
FFP3 (untreated)	50	5	5.506	0.357	H0
FFP3 (treated)	50	7	0.484	1.000	H0

FFP, filtering facepiece.

example, the penetration of untreated FFP2 respirator of the brand A under high concentration is even greater than the FFP1 respirator under the same conditions; the similar situations can be found by treated FFP2 respirator of the brand A and treated FFP3 respirator of brand B under both concentrations.

The regression analysis between the flame photometer and the PortaCount for all tested respirators ($n = 72$) is shown in Fig. 10 and the regression analysis between the flame photometer and the PortaCount with the N95-Companion™ ($n = 72$) is shown in Fig. 11. The results of the regression analysis between the tested instruments according to the treatment of the respirators are shown in Fig. 12.

The PortaCount did exhibit a penetration higher than the penetration shown by the flame photometer. There is a linear relationship between the PortaCount and the flame photometer ($R^2 = 0.9704$) for all tested respirators (see Fig. 10). When only the filter penetration (untreated mask) is considered, the linear relationship is still existent ($R^2 = 0.9054$) between two instruments (see Fig. 12). These observations are consistent with previous reports, which compared a count-based method to a mass-based method with respect to filter penetration [26–28]. This correlation between both methods tested in this study was independent of particle concentration level, filter class, and penetration level, which suggested that PortaCount alone could be an appropriate alternative instrument of the flame photometer used for measuring WPF under workplace conditions.

Between the PortaCount with the N95-Companion™ and the flame photometer, a linear regression can also be found ($R^2 = 0.9754$) (see Fig. 11). Furthermore, the results of the PortaCount with the N95-Companion™ are comparable with those of the flame photometer. However, it should be noted that the linear relationship is none existent when the mask is untreated ($R^2 = 0.5050$) (see Fig. 12). The reason for this lies in the measuring principle of the N95-Companion™. As the PortaCount with the N95-Companion™ measures only the particles that pass through the face seal leakage, when only filter penetration exists, the particle behind the respirator can be hardly detected by the PortaCount with the N95-Companion™.

Two recent surveys have tested portable instruments for the sake of selecting a portable instrument, which can be used for evaluating nanoparticle exposure at workplaces. Vo et al. [29] compared three portable aerosol instruments to a reference SMPS with monodispersed and polydispersed aerosols under laboratory conditions. One of the three tested portable instruments is handheld CPC (TSI Inc., Model 3007), which is a similar instrument to the PortaCount. The result showed that aerosol concentration measured with the CPC was approximately 30% lower than that measured with the SMPS and a linear relationship ($R^2 = 0.98$) was found between the CPC and the reference SMPS. A possible reason may be the low accuracy of the CPC. Zhuang et al. [30] compared a CPC (TSI Inc., Model 3007) and a portable aerosol mobility spectrometer (PAMS 3310) (Kanomax, Osaka, Japan) with a reference

Table 2
Results of Chi-square test of respirators from brand B

Mask (Treatment)	Sodium chloride solution [μS/cm]	df	Chi-square statistic	Asymptotic significance	Hypothesis
FFP1 (untreated)	100	6	20.031	0.003	H1
FFP1 (treated)	100	7	0.87	0.997	H0
FFP2 (untreated)	100	5	10.824	0.055	H0
FFP2 (treated)	100	7	0.594	0.999	H0
FFP3 (untreated)	100	3	0.531	0.912	H0
FFP3 (treated)	100	7	4.584	0.711	H0
FFP1 (untreated)	50	6	156.648	0.000	H1
FFP1 (treated)	50	7	121.681	0.000	H1
FFP2 (untreated)	50	5	5.258	0.385	H0
FFP2 (treated)	50	7	0.114	1.000	H0
FFP3 (untreated)	50	3	2.176	0.537	H0
FFP3 (treated)	50	7	0.675	0.999	H0

FFP, filtering facepiece.

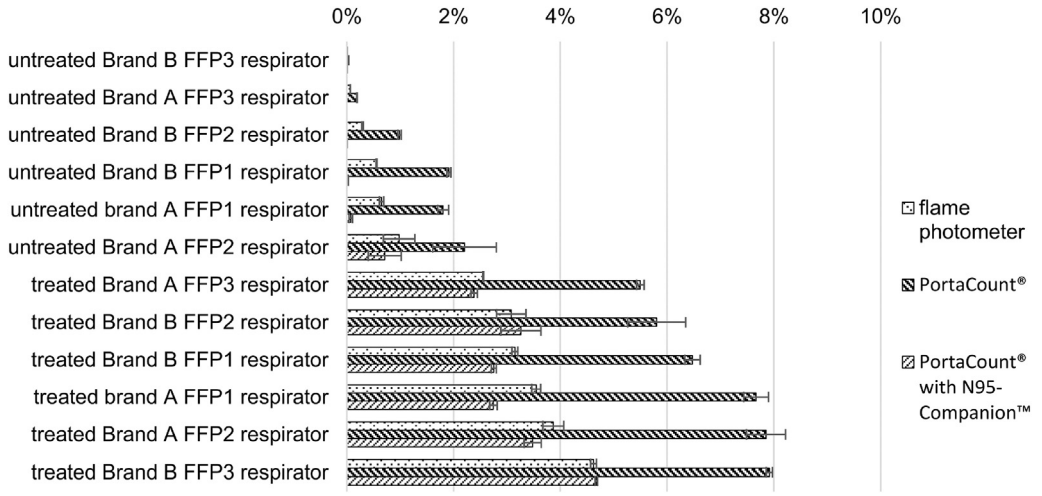


Fig. 8. Penetration results of flame photometer and the PortaCount and the PortaCount with the N95-Companion™ under high concentration.

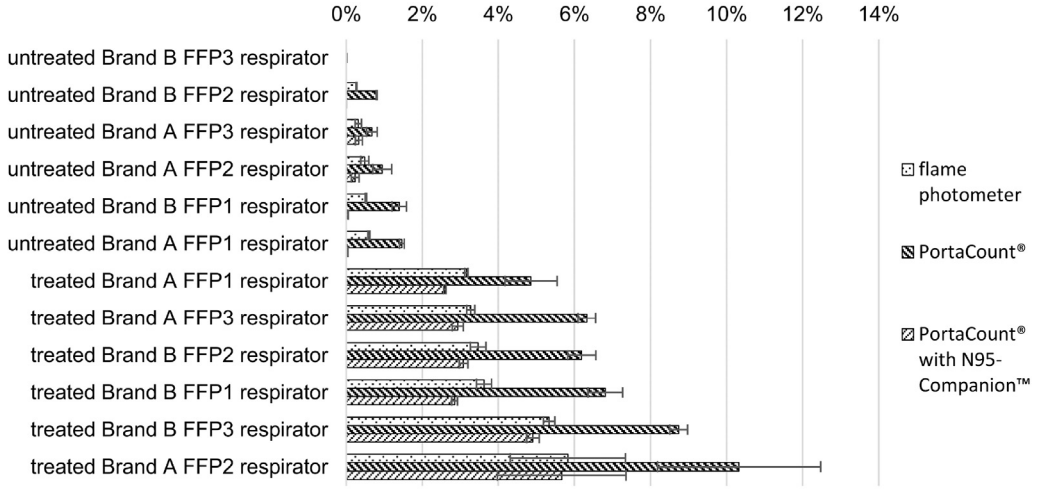


Fig. 9. Penetration results of flame photometer and the PortaCount and the PortaCount with the N95-Companion™ under low concentration.

TSI SMPS under simulated workplace conditions. Eight test subjects performed simulated exercises while wearing N95 filtering facepiece respirator. Two CPCs (or two PAMSs) and the reference SMPS measured particles outside and inside the respirator and simulated workplace protection factor (SWPF) were calculated. This study found that the SWPF measured with the CPC was correlated ($R^2 = 0.70$) with the SWPF measured with the reference SMPS. The

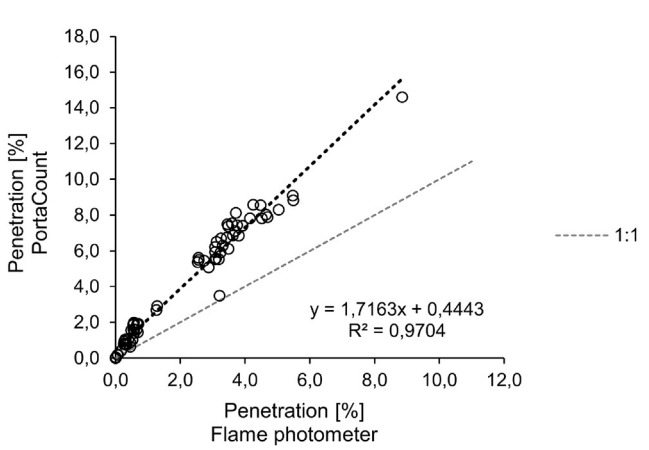


Fig. 10. Regression analysis between the flame photometer and the PortaCount.

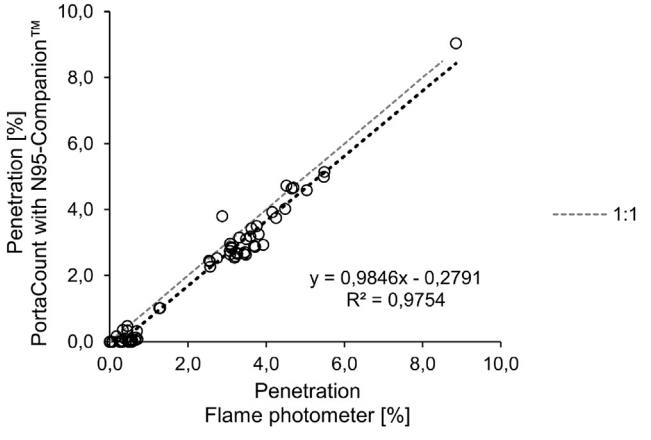


Fig. 11. Regression analysis between the flame photometer and the PortaCount with the N95-Companion™.

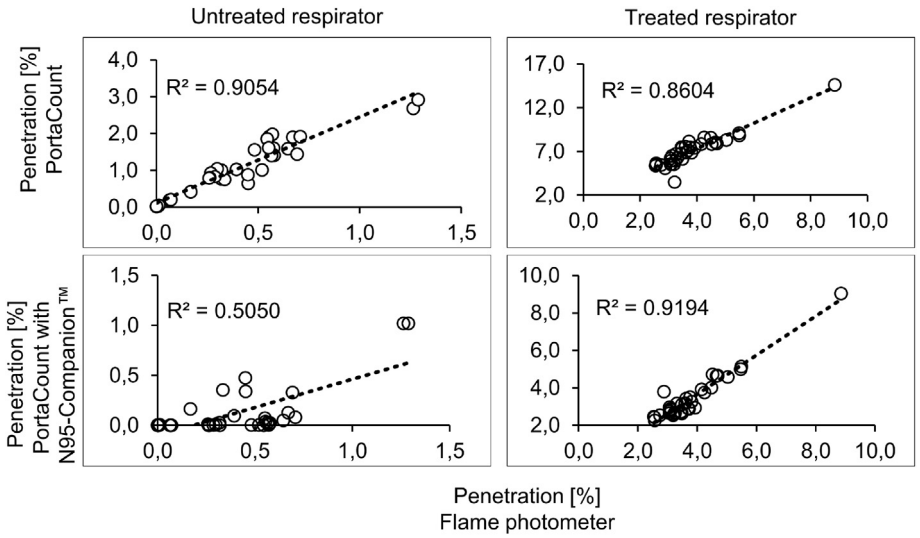


Fig. 12. Regression analysis between the flame photometer and the PortaCount with/without the N95-Companion™ for treated and untreated respirators.

findings in these studies support that CPC measuring instrument (e.g., PortaCount) could be selected as a suitable instrument for aerosol measurement in the workplace.

However, Janssen et al. [3] addressed several concerns about using direct-reading measuring instruments for collecting WPFs. It is noted that samples collected using direct-reading instruments are usually for a short period, which may not be representative for the real exposures and WPFs. Moreover, differences exist in calculation of WPFs between using direct-reading instruments and using traditional method with, e.g., personal sampling pumps and filter cassettes. Therefore, it is currently not clear how the WPFs collected using direct-reading instruments should be compared with WPFs collected using traditional methods.

Some limitations should be noted. It has been shown that fixed face seal leakages may not be representative for individuals wearing respirator [3]. The leakage results obtained in this study may be influenced by different leakage sizes and respiratory pattern. Another limitation was the aerosol generated in the laboratory conditions, which could differ from the aerosol at workplaces. However, the laboratory leakage results in this study were collected under "worst-case" conditions by using high flow rate and polydisperse sodium chloride aerosol, which provide meaningful data for selecting a portable instrument for WPF measurements.

4. Conclusions

In this study, correlations were found between the PortaCount (with and without the N95-Companion™) and the flame photometer. The linear relationship was observed between the PortaCount and the flame photometer under all test conditions, the PortaCount showed approximately double penetration results compared with the penetration results of the flame photometer. When the PortaCount was assembled with the N95-Companion™, the linear relationship could be still found. However, if the respirator was untreated (only filter penetration), the PortaCount with the N95-Companion™ delivered implausible results. The changes of the particle size distribution inside the respirator compared with the particle size distribution outside the respirator were detected only in 4 cases (of total 24 cases), that might be related to the filter material and/or testing instrument. In most cases, there was no change in the particle size distribution inside and outside the respirator, which validate the correlation between the PortaCount (with and without the N95-Companion™) and the flame photometer.

Based on the results of this study, the PortaCount (without N95-Companion™) may be a good alternative measuring device of the flame photometer for determination of workplace protection factor.

Conflicts of interest

All authors have no conflicts of interest to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.shaw.2019.11.001.

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