Real-time performance of filtering facepiece respirators at the workplace

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ABSTRACT The efficacy of a respirator under real workplace conditions is presented by its workplace protection factor (WPF). The aim of this study was to assess a portable measuring system for the determination of WPF for particulate filtering facepiece respirators. WPFs of CE-marked FFP2 and FFP3 filtering facepiece respirators were measured as a pilot test conducted at two workplaces: an inter-company training facility and a paper mill, with a total of seven test subjects. Each subject was quantitatively fit tested prior to the field measurements. Two TSI PortaCount instruments measured the particle concentrations simultaneously and continuously inside and outside the respirator for 15 min, with three repetitions. The results of the fit test (overall fit factor) ranged from 22 to 199. Individual WPF results ranged from 16 to 568 for FFP2 respirators, and from 13 to 232 for FFP3 respirators. The geometric means (GM) of the WPF were 135 with a 5^{th} percentile value of 37 (FFP2), and 47 with a 5^{th} percentile value of 12 (FFP3). This pilot test provides a new method of evaluating the workplace performance of filtering facepiece respirators.

Echtzeit-Performance partikelfiltrierender Halbmasken am Arbeitsplatz

ZUSAMMENFASSUNG Das Schutzniveau einer Atemschutzmaske unter realen Arbeitsplatzbedingungen wird durch ihren Arbeitsplatzschutzfaktor (workplace protection factor, WPF) beschrieben. Ziel dieser Studie war es, ein tragbares Messsystem zur Bestimmung von WPF partikelfiltrierender Halbmasken zu bewerten. Die WPF von CE-gekennzeichneten FFP2- und FFP3-Masken wurden als Pilotversuch an zwei Arbeitsplätzen gemessen: einer überbetrieblichen Ausbildungsstätte und einer Papierfabrik mit insgesamt sieben Probanden. Der Dichtsitz der Maske wurde bei jeder Person vor den Feldmessungen bestimmt. Mit zwei TSI PortaCount-Geräten wurde die Partikelkonzentrationen gleichzeitig und kontinuierlich innerhalb und außerhalb der Maske für 15 min gemessen, mit drei Wiederholungen. Die Ergebnisse der Dichtsitzprüfung (Gesamt-Fit-Faktor) lagen zwischen 22 und 199. Die einzelnen WPF-Ergebnisse lagen zwischen 16 und 568 für FFP2-Masken sowie zwischen 13 und 232 für FFP3-Masken. Die geometrischen Mittel (GM) des WPF betrugen 135 mit einem 5-Perzentil-Wert von 37 (FFP2) und 47 mit einem 5-Perzentil-Wert von 12 (FFP3). Dieser Pilotversuch bietet eine neue Methode zur Bewertung des Schutzniveaus von partikelfiltrierenden Halbmasken am Arbeitsplatz.

1 Introduction

Respiratory protective devices (RPDs) protect employees against airborne contaminants in the working environment, and the particulate filtering facepiece respirators are a widely used RPD in a broad range of industries. European certified CE-marked particulate filtering facepiece respirators are assigned to three classes: FFP1, FFP2, and FFP3. This classification is based on laboratory tests, which include testing of the respirators' filtering efficiency and their total inward leakage (TIL) [1]. According to European standards, the TIL consists of face seal leakage, filter penetration and exhalation valve leakage (where the respirator features an exhalation valve) [1]. The TIL should be determined by measuring the mass concentration of the tested aerosol inside and outside the respirator. The TIL of an FFP1 respirator is 22% with a maximum filter penetration of 20%; the TIL of an FFP2 respirator is 8% with a maximum filter penetration of 6%; for FFP3 respirators, the TIL should be equal or less than 2% and the filter penetration should be equal or less than 1%. It follows that of these three classes, the FFP3 respirator should provide the best protection. Laboratory test conditions differ from realistic working conditions; the performance of a respirator in the laboratory cannot therefore perfectly represent the protection provided by it at the workplace [2]. Hence, it is essential for the performance of a respirator at the workplace to be verified there. The assigned protection factor (APF) is a term used to indicate the expected protection level of a respirator at the workplace that can be achieved by 95% of the respirator wearers [2]. The APF should be determined based upon the lower 5^{th} percentile of workplace protection factor (WPF) [3]. The WPF represents the protection level delivered by a respirator that is functioning correctly when worn and used in the workplace [2]. It covers both face seal leakage and filter penetration [4 to 6] and takes the form of the ratio of the hazardous substance concentrations outside and inside the respirator.

WPF data are helpful for providing a more detailed understanding of the respirator performance at the workplace, and at present is important for the determination of a reasonable APF. However, there is no standardized test procedure for the determination of WPFs of particulate filtering facepiece respirators to the best of our knowledge. This leads to discrepancies in APF values between different European countries, even for the same class of respirator. A few WPF studies have been published over the past decades [7 to 13]: in these studies, a personal sampling pump and filter cassette were used as a method of sampling outside and inside the respirator, and the respirators tested were N95 filtering facepiece respirators and half-facepiece respirators of the types used in the USA. However, this method determines the mass concentration of particles, which may lead to a relatively long sampling period [7]. At the same time, little attention has been paid to workplace measurements on the FFP respirators used and approved in Europe.

In order to investigate the workplace performance of FFP respirators, a condensation particle counter (CPC), which is known for the good correlation with scanning mobility particle sizer (SMPS) under simulated workplace conditions [14], was chosen as a suitable measuring method for determining the WPF. PortaCount 8020 (TSI Inc., Shoreview, Minnesota, USA) was the selected instrument for this work, which has already been used in simulated workplace studies [5; 6; 15 to 17] and has been validated against the reference method (flame photometer) under laboratory conditions (manuscript submitted for publication). In this paper, we present a pilot study of WPF measurements using the PortaCount system as a measuring system.

2 Materials and methods

2.1 Instrument validation

The PortaCount system is a CPC with a measuring range from 0.01 to 5 × 10^5 particles/cm^3 [18]. To enable it being used under workplace conditions as a portable instrument, it should be carried vertically by subjects during the work, rather than horizontally as is normally the case.

To verify whether the change in orientation had a significant impact on the data acquired by the PortaCount counters, two laboratory experiments were conducted in which the orientations were compared. In the first experiment, one system was tested in the two orientations alternately for a short period of time (1 min) at four particle concentrations. The tested PortaCount measured each particle concentration for 10 min and the orientation of PortaCount was changed every minute. In the second experiment, two PortaCount counters were tested continuously and simultaneously over a long period of time (15 min) at three particle concentrations, one counter being used vertically, the other one horizontally. Each 15-min test was repeated twice and the orientation was changed. The measured data from the counters were recorded at intervals of one second.

2.2 Field measurement

2.2.1 Sites and respirators

The field study was carried out at two sites: a training facility for metalworking and electrical occupations and a paper mill. In the training facility, three tasks were selected as work activities for testing: manual metal arc welding, turning, and gas metal arc welding. Nevertheless, the use of respirators is not mandatory in the training facility. The trainees therefore were not medically assessed in order to determine whether their use of FFP3 respirators was permissible. For this reason, FFP2 respirators were selected for the test subjects (trainees) in the training facility. In contrast, use of an FFP3 respirator was mandatory in the paper mill. FFP3 respirators were therefore prepared for the test subjects in the paper mill. WPF measurements were carried out in a paper sorting plant at the paper mill in which waste paper, cardboard and other waste was delivered to workers by conveyor belt, and sorted manually.

Figure 1. Subject equipped with the measuring instrument (PortaCount).

Two major brands of CE-certified FFP2 and FFP3 respirator on the German market (brands A and B) were used for the workplace measurements. The brand A respirators are cup-shaped and available in two sizes, namely S and M/L. The brand B respirators are folded and available in one size. FFP2 respirators from brand A (sizes S and M/L) were tested at the training facility. FFP3 respirators from brand A (size S) and brand B were tested at the paper mill.

2.2.2 Test subjects

Overall, seven male test subjects participated in the workplace measurements: two trainees from the training facility (hereafter referred to as #1 and #2) and five workers from the paper sorting plant at the paper mill (hereafter referred to as #3 to #7).

The test subjects were aged between 19 and 45 years. Five workers at the paper mill had experience of using the filtering facepiece respirator varying from one month to five years, whereas two trainees from the training facility had no experience.

Ten facial dimensions were measured in accordance with ISO/TS 16976-2 [19] using a digimatic caliper in order to identify the cell of each subject in the principal component analysis (PCA) panel. In this study all facial dimensions of each subject were measured once.

2.2.3 Fit test

The aim of a fit test is to verify, by examination of the face seal leakage, that a selected respirator fits the wearer. For FFP2 and FFP3 respirators, a required fit factor (FF) of 100 is specified in an ISO standard [20]. In order to explore the relationship between FFs and WPFs, the fit test was conducted in this study.

It was performed using the PortaCount 8020 in combination with an N95-Companion electrostatic classifier, which enables only face seal leakage to be assessed. According to ISO/DIS 16975-3.2 subsection 8.4, each test involved seven exercises:

- Normal breathing,
- Deep breathing,
- Head side to side,
- Head up and down,
- Talking loudly,
- Bending over,
- Normal breathing [20].

Each exercise lasted one minute and a completed fit test was performed once prior to the WPF measurement for each combination of test subject and activity. An overall FF was recorded manually at the end of the test.

The test was conducted in a separate room from where the WPF measurements were carried out. A particle generator (Model 8016, TSI Inc., Shoreview, Minnesota, USA) was used to ensure an ambient particle concentration > 100 particles/cm³ [21]. It is recognized that cigarette smoking can lead to an inaccurate fit factor [21]; this premise was taken into account, and the subjects refrained from smoking for at least 30 min prior to the fit test.

FFP2 respirators (brand A in sizes S and M/L) were assigned to the test subjects in the training facility. As explained above, the use of a respirator during work was not mandatory. The required fit factor of 100 was not taken into consideration and the subjects' participation in the further WPF measurements was not determined by the results of their fit tests.

FFP3 respirators (brand A in size S and brand B) were tested in the paper mill. None of the test subjects at the paper mill had experience with the particular respirators used in this study. To ensure sufficient protection for the test subjects during the workplace measurements, the fit test requirement was taken into account, and only test subjects who passed the fit test (FF higher than 100) were allowed to participate in the WPF measurements. Seven workers initially expressed interest in taking part in this study, in which two failed the fit test with both respirator models provided. WPF measurements were therefore conducted in the paper mill on only five test subjects.

2.2.4 WPF Measurement

Each test subject from the training facility performed all three tasks (manual metal arc welding, turning, and gas metal arc welding) and each test subject from the paper mill performed sorting of paper. Particle concentrations inside (C_i) and outside the respirator (C_o) were measured during the work simultaneously and continuously at intervals of one second by two PortaCount counters (Model 8020).

In order for the measuring instrument (PortaCount 8020) to be transportable and thus not interfering with the routine work of the test subjects, three modifications were performed. Firstly, a carrier system was designed to enable the test subjects to be fitted with the counters (**Figure 1**). The carrier system consists of shoulder and waist straps and a plastic plate, in combination resembling a backpack. The shoulder and waist straps are adjustable and the instruments can be fixed to the plastic plate by Velcro straps. The whole system including instruments weighs approximately 5 kg. Secondly, the PortaCount counters were modified, and each counter was equipped with a Bluetooth adapter permitting wireless connection to a computer. DasyLab software (National Instruments, Austin, Texas, USA) was employed for control of the instruments and the acquisition of measurement data. DasyLab enables the data from PortaCount counters to be recorded and visualized at intervals of one second by means of a layout designed for the purpose. Thirdly, the PortaCount counters were powered by a specially designed battery (approx. 0.4 kg) that ensured continuous operation for up to three hours.

Each combination of subject and task was measured three times for 15 min each time. To obtain a representative estimate of the WPF over the entire working time, these three measurements should be distributed as evenly as possible over the working hours of the test subject.

To ensure a consistent (±15%) result from two PortaCount instruments, a test measurement was taken shortly before WPF measurements of each subject were started. The test measurement lasted 30 sec and was conducted in the same room in which the WPF measurements were carried out.

The performance of a respirator used at a workplace can be affected by other factors, such as work activities and personal behavior. To aid observation of the work process and personal behavior, WPF measurements were recorded by means of video surveillance. The recorded video can be synchronized with the measured data from PortaCount by the WIDAAN software (IFA, Sankt Augustin) developed for the purpose.

2.2.5 Data Analysis

For comparing the particle concentrations measured by horizontal and vertical PortaCount, arithmetic means were calculated of each one-min period for plotting the data. Linear regressions were performed between one-min mean values from horizontal PortaCount and vertical PortaCount using Microsoft Excel 2016.

The WPF was calculated by dividing the 15-min mean value of the particle concentration outside the respirator by the value inside the respirator. The measured WPF data were compared to the specified APF by means of a descriptive, non-statistical model. The ln-transformed WPF data (n = 33) was tested by the *Kolmogorov-Smirnov* test for normality and it exhibited a log-normal distribution (p = 0.099); the geometric mean (GM) and the geometric standard deviation (GSD) of WPFs were determined. The lower 5th percentile of WPFs was determined based on the GM and GSD by the formula $GM/GSD^{1{,}645}$ [16; 22 to 24].

The FF data (n = 11) exhibited also a log-normal distribution (*Kolmogorov-Smirnov* test p = 0.135). A linear regression of

$\log_{10}$-transformed FF and mean $\log_{10}$-transformed WPF (n = 3) was performed for all subject/activity combinations.

3 Results

3.1 Instrument orientation test

The results of two experiments by means of scatterplots are shown in **Figures 2 and 3** respectively; each point in the figures represents the mean value over a period of one minute.

The measured data from one PortaCount in both orientations were overlapped with the reference line (Figure 2). A regression analysis between the horizontal and vertical PortaCount shows that there was a highly linear relationship ($R^2 > 0.99$) between the particle concentration measured by horizontal PortaCount and vertical PortaCount for a short period of time (1 min).

In the second experiment, the data from the vertically oriented counter were similar to those from the horizontally oriented counter (Figure 3). The regression analysis shows that there was a highly linear relationship between particle concentration measured by horizontally oriented one and vertically oriented counter 2 with the coefficient R^2 = 0.9992. Similar relationship (R^2 = 0.9983) was also found *vice versa*. However, it should be noted that the data plotted from the highest particle concentration in one test (vertical PortaCount 1 vs. horizontal PortaCount 2) showed a slight deviation from the reference line, in which the vertically oriented instrument presented a higher particle concentration than its horizontally oriented counter. One possible reason is that the highest tested particle concentration already exceeded 4.5×10^5 particles/cm³, which is the upper limit of the PortaCount measuring range and may hence cause higher fluctuation in the measured data.

These experimental results confirm that the PortaCount system is able to function properly in a vertical orientation.

3.2 Field measurement results

WPF measurements conducted during two welding activities yielded instantaneous particle concentrations outside the respirator above the upper limit of the PortaCount measuring range. The results exceeding the measurement range were assumed as unreliable. Therefore, concentrations outside the respirator exceeding 5×10^5 particles/cm³ and the corresponding concentrations inside the respirator were disregarded.

Particle concentrations outside and inside the respirator for all tested tasks are shown in **Figure 4**. It can be seen that the use of a respirator significantly reduced the particle concentration inhaled, two orders of magnitude in every working activity. As expected, concentrations outside the respirator varied significantly between different tasks. It is evident that the outside particle concentration produced during welding processes (manual metal arc welding and gas metal arc welding) was considerably higher than that produced by other work activities. The mean concentration generated from manual metal arc welding and gas metal arc welding were 139,308 and 156,231 particles/cm³ respectively, however, the mean concentration generated from turning and paper sorting were only 46,697 and 10,498 particles/cm³. Furthermore, during the welding process, particle concentrations outside the mask fluctuated more strongly than during other work processes, relating to the variability in this kind of work. In **Figure 5** the concentrations (recorded every second) outside the respirator, for manual metal arc welding and paper sorting, are presented. The observed peaks are quite normal for a welding activity,

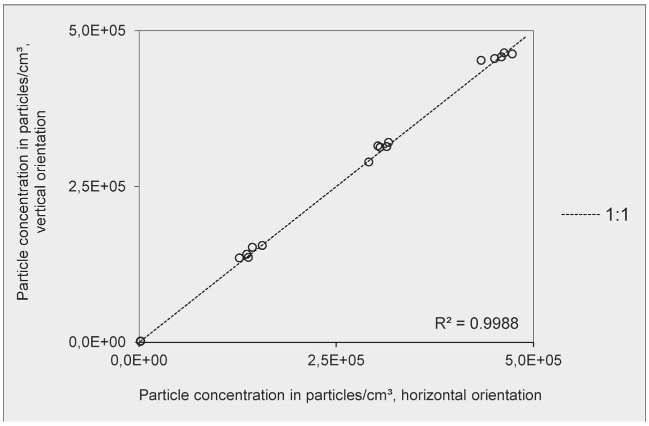

Figure 2. One PortaCount counter tested alternately in different orientations for one min.

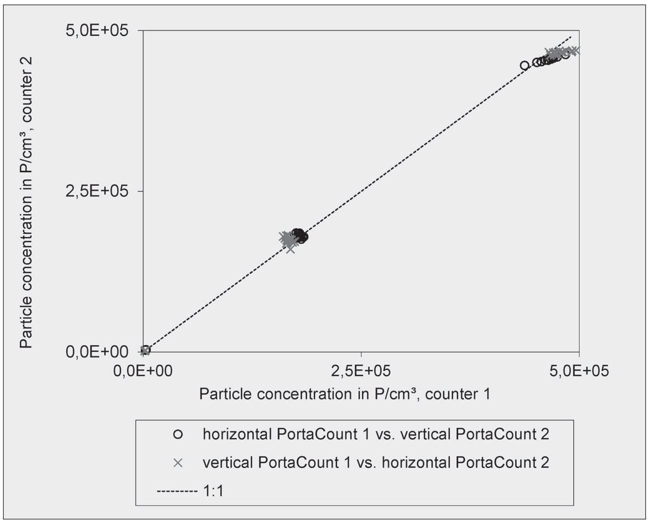

Figure 3. Two PortaCount counters tested simultaneously in different orientations for 15 min.

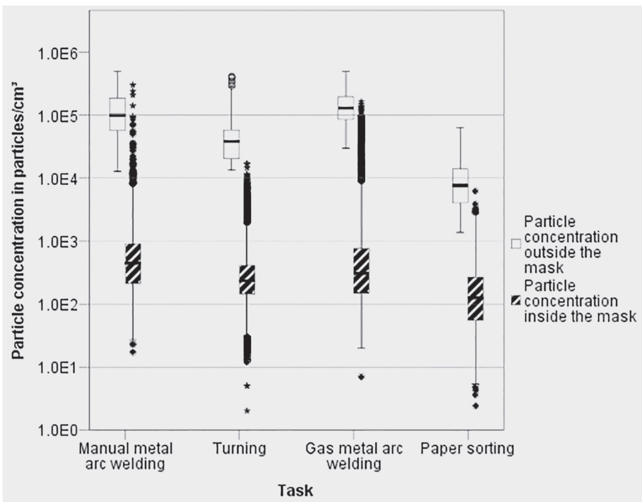

Figure 4. Particle concentrations outside and inside the respirator for all tested tasks.

which is usually carried out in short intervals of welding, for a determinate period.

The results of overall FF for each subject/task combination are summarized in **Tables 1 and 2** for FFP2 and FFP3 respirators respectively. In general, the overall FF varied widely between different test subjects and ranged from 22 to 199. Test subjects #1 and #2 at the training facility both failed the fit test with the FFP2 respirator, and their overall FF varied between 22 and 77. At the paper mill, the overall FF of test subjects varied between 105 and 199.

The WPF results with the mean value of particle concentrations (outside/inside the facepiece) over 15 min and the GM of real-time WPF are summarized in Tables 1 and 2. Thirty-three workplace measurements were conducted, including 18 measurements with the FFP2 respirator (Table 1) and 15 measurements with the FFP3 respirator (Table 2).

As mentioned previously, three WPF measurements were taken for each subject/activity combination and the measurements should be distributed over the test subject's working hours. In practice, however, due to the working time arrangements (e.g. shift work) and demands of work efficiency, it was not always possible for the WPF measurements to be distributed over the full working hours. At the training facility, the three measurements for one combination of subject and activity were almost evenly distributed over 4 h, whereas the planned working time of subjects was 6.5 h. At the paper mill, however, this was not achieved due to time restrictions; the measurements in the paper mill were consequently evenly distributed over a little under 1.5 h. For the FFP2 respirator, the WPF values ranged between 16 and 568 and the mean WPF value was 174 (n = 18). All measured WPF values were higher than the APF specified for Germany as VdGW in the DGUV Rule 112-190 [25] for FFP2 respirators (APF = 10). The geometric mean (GM) was 135 (GSD = 2.18). The lower 5th percentile of WPFs for the FFP2 respirator in this study was therefore 37, which is considerably higher than the APF required for the FFP2 respirator.

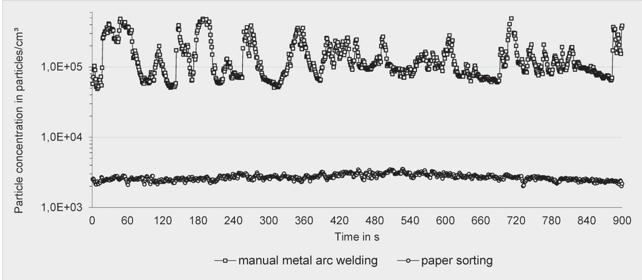

Figure 5. Particle concentrations outside the respirator (extracted from one measurement) for manual metal arc welding and paper sorting.

For the FFP3 respirator, the WPF values varied between 13 and 232, with a mean WPF value of 65. The GM for measurements of the FFP3 respirator was 47 and the GSD was 2.33. Of all 15 workplace measurements, four measurements (approximately 27%) were lower than the specified APF for the FFP3 respirator (APF = 30). The lower 5th percentile of WPFs for the FFP3 respirator in this study was only 12, which was well below the APF specified for the FFP3 respirator.

The linear regression of the $\log_{10}$-transformed FF and mean $\log_{10}$-transformed WPF (n = 3) for all subject/activity combinations indicated a weak correlation between FF and WPF (R^2 = 0.161) (see **Figure 6**).

4 Discussion

In earlier studies, attempts were made to test the performance of particulate filtering facepiece respirators by means of Porta-Count counters [5; 6; 15 to 17]. However, these studies either evaluated the performance of respirators in simulated exercises, or were conducted under simulated workplace conditions. In this study, we tested the performance of particulate filtering facepiece respirators at workplaces by mean of two CPCs. This is therefore

Table 1. Summary of overall FF and WPF results of FFP2 respirator.

Subject	Task[1]	Overall FF	R[2]	FFP2 Respirator Brand (Size)	Data points	Particle concentration in particles/cm³ C_0	C_i	WPF C_0/C_i	GM real-time WPF
#1	MW		1	A (M/L)	774	192,945	2,530	76	377
#1	MW	25	2	A (M/L)	899	61,640	403	153	177
#1	MW		3	A (M/L)	897	161,021	990	163	204
#1	TN		1	A (M/L)	898	76,221	711	107	198
#1	TN	22	2	A (M/L)	900	29,847	146	205	272
#1	TN		3	A (M/L)	900	55,899	409	137	171
#1	GW		1	A (M/L)	868	148,508	761	195	497
#1	GW	77	2	A (M/L)	868	175,152	392	447	705
#1	GW		3	A (M/L)	880	168,398	296	568	739
#2	MW		1	A (S)	724	231,947	2,772	84	144
#2	MW	62	2	A (S)	896	75,198	367	205	277
#2	MW		3	A (S)	881	138,402	907	153	184
#2	TN		1	A (S)	900	21,363	200	107	117
#2	TN	65	2	A (S)	900	43,605	553	79	100
#2	TN		3	A (S)	900	53,311	417	128	130
#2	GW		1	A (S)	838	167,362	2,303	73	218
#2	GW	32	2	A (S)	855	166,392	10,648	16	40
#2	GW		3	A (S)	872	112,145	468	240	446

[1] MW = manual metal arc welding, TN = turning, GW = gas metal arc welding
[2] Repetition

Table 2. Summary of overall FF and WPF results of FFP3 respirator.

Subject	Task[1]	FF	R[2]	FFP3 Respirator	Data points	Particle concentration in particles/cm³		WPF	GM real-time WPF
				Brand (Size)		C_0	C_i		
#3	PS	151	1	B	900	28,966	354	82	113
#3	PS		2	B	900	14,899	135	111	142
#3	PS		3	B	900	8,766	244	36	48
#4	PS	105	1	B	900	5,186	399	13	15
#4	PS		2	B	900	4,346	284	15	17
#4	PS		3	B	900	5,305	381	14	15
#5	PS	199	1	A (S)	900	2,675	106	25	35
#5	PS		2	A (S)	900	2,085	54	39	43
#5	PS		3	A (S)	900	1,956	40	49	61
#6	PS	194	1	B	900	17,928	77	232	402
#6	PS		2	B	900	12,070	151	80	102
#6	PS		3	B	900	4,656	157	30	52
#7	PS	106	1	A (S)	900	8,993	77	116	141
#7	PS		2	A (S)	900	27,859	383	73	95
#7	PS		3	A (S)	900	11,786	202	58	69

[1] PS = paper sorting
[2] Repetition

to our knowledge the first study applying PortaCount counters to evaluate the workplace performance of a respirator.

In this study, FFP2 respirators provided sufficient protection during work in terms of the APF 1. These results are comparable with those obtained by *Kim* and other researchers by use of the N95 respirator [13; 16; 26; 27], since the N95 respirator is comparable in its filter penetration to the FFP2 respirator. During measurements, the FFP2 wearers were, for the most part, performing work activities whilst seated, which ensures a better fit and lower likelihood of face seal leakage. In contrast, the test subjects wearing FFP3 respirators performed broader body movements while standing, implying the transport of light items, speaking, and torso rotation, as recorded in our video surveillance system. By our understanding, this gives rise to an increased face seal leakage, which would explain the lack of protection determined by our measurement, namely a lower WPF than expected.

The correlation between FFs and WPFs has been broadly discussed [9; 11; 12; 28]. The conclusion is that the correlation is low [9; 28], which at first glance could also be the case for this paper. Nevertheless, several reasons have been documented for these findings. Among other reasons, *Zhuang* et al. [11] state differences in donning the respirator as a factor for this low correlation, which is also the reason most applicable to our test situation. Another practical aspect that applies only to our study may be the fact that, for technical reasons, the fit factor results of each exercise were limited to 200. This may affect the statistical overall FF, which in turn affects the correlation between FFs and WPFs.

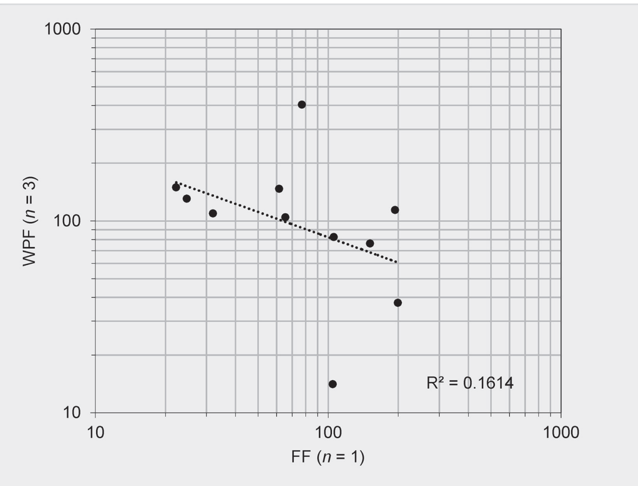

Figure 6. Plot of WPFs against FFs with the regression line.

This study is thus the first to test workplace performance of FFP respirators by means of PortaCount counters. Certain limitations should nevertheless be noted. The results obtained may not be representative for all respirator wearers, since the test subjects were concentrated mainly in cells 1, 2 and 4 of the PCA panel, which did not encompass the full PCA panel. Performance of workplace measurement is known to be very difficult [16; 29 to 31], permission must be obtained to access enterprises, and at the same time, considerable time and manpower are required of research groups and participating enterprises alike. For these reasons, only a limited number of workplace measurements could be carried out during the period of this study, resulting in limited data volumes.

Nevertheless, the innovative measuring method developed constitutes a practical method for determining the actual protection level of a particulate filtering facepiece respirator at a workplace and enables factors potentially influencing the WPF to be determined.

5 Conclusions

This study was the first to evaluate the workplace performance of FFP2 and FFP3 respirators using a portable WPF measuring method, namely PortaCount. In the study, WPF measurements were conducted and allocated to seven subjects performing four different types of occupational activity, including 17 measurements with an FFP2 respirator and 18 measurements with an FFP3 respirator. The results show an arithmetic mean of WPF values of 174 for an FFP2 respirator but only 65 for an FFP3 respirator, which on the basis of its normative classification ought to provide better protection. We thus present a novel and user friendly measurement method for workplace protection factors, with good correlation to the standardized test instrument (manuscript submitted for publication), that shows a promising performance in workplace measurements.

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