보건학석사 학위논문

A Study on the Correlation Between Static Electricity and Filtration Efficiency of Particulate Respirators

산업용 및 보건용 마스크의 정전기와 여과효율의 상관성에 관한 연구

2021년 8월

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지도교수 윤 충 식

이 논문을 보건학석사 학위논문으로 제출함
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Abstract

A Study on the Correlation Between Static Electricity and Filtration Efficiency of Particulate Respirators

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Introduction Respirators have been widely used to protect workers' health from airborne chemicals and bioaerosols in the workplace. However, due to environmental factors such as yellow dust and fine dust, it has become common for workers as well as all residents to wear masks. Aerosols are absorbed in the respirator via various mechanisms such as gravity sedimentation, inertial impaction, interception, diffusion, and electrostatic attraction. However, increasing the efficiency of the respirator filter causes the pressure drop to increase as well, which can be a problem. By adding static electricity to the respirator, the efficiency can be improved while maintaining an almost constant pressure drop. However, static electricity could be reduced when exposed to moisture for a long time. Contact with charged particles also reduces static electricity. The objective of this study was to evaluate the electrostatic properties and filtration efficiency of respirators according to their age, changes in ambient humidity and temperature, and the mask-wearing duration. Furthermore, this study compared occupational-use and public-use of respirators.

Methods Respirators from four manufacturers were selected for this study, and two types of respirators from each manufacturer were tested; occupational-use respirators (1st class) and public-use respirators (KF-94). First, in order to observe how much static electricity contributes to filtration efficiency, static electricity was removed. To study the effect of time, the respirator was exposed to mask-wearing temperature (38°C) and humidity condition (85%) for 8 hours, and subsequently stored at room temperature (20°C, 50% RH) for 16 hours per day. This was repeated for 1, 2, 4, and 8 d. To study the effect of humidity and temperature on the efficiency of the masks, i) the temperature was fixed at 25℃, and the samples were exposed to humidity of 30, 50, and 98%, and ii) humidity was fixed at 50%, and samples were exposed to temperatures of –30, 50, and 70℃. Finally, ten participants were recruited for this study, who had actually worn masks for a significant duration. The respirator was collected after wearing it for 1, 2, or 4 d. While wearing, the gender, wear time, and behavioral changes were recorded among the participants. The static electricity on the surface of the respirator and on each inner layer filter (sampled after cutting the respirator) were measured using a surface potential meter, and the filtration efficiency was measured for NaCl and paraffin oil using a filter tester.

Results Owing to the removal of static electricity from respirators, the filter efficiency of 1st class and KF-94 respirators decreased by 21.72% and 19.53%, respectively. Over time, a decrease in static electricity was observed in all respirators except for one product, and a decrease in filtration efficiency was also observed in one KF-94 ($p<0.001$). The filter efficiency decreased to less than 94% after 8 d. Both static electricity and filter efficiency decreased according to humidity, and the decrease was significant in both 1st class and KF-94 ($p<0.05$) respirators. The static electricity and filtration efficiency did not differ significantly according to temperature ($p>0.05$), unlike humidity conditions. There was a decrease in filtration efficiency for only one KF-94 ($p<0.05$). The masks that were actually worn by the participants exhibited a decrease in static electricity and filtration efficiency by 11.26% and 6.51%, respectively, as the wearing duration increased. The pressure drop also decreased with increasing time (10.29%). Correlation analysis indicated a strong positive correlation between static electricity and filtration efficiency with respect to changing humidity; however, the correlation was weaker at variable temperature conditions. The decrease in the filtration efficiency of respirators in high humidity environments can be explained by the reduction in static electricity, however, the decrease in filtration efficiency at high temperatures was found to be the result of deformation of respirator properties rather than effect of static electricity.

Conclusion The rate of decrease in static electricity and filtration efficiency of respirator was the highest for increasing humidity, followed by increasing time lapse and temperature. We suggest that the results of this study should be considered while testing a mask. Furthermore, technological advances are required in the future for retaining static electricity inside respirator filter.

Keyword: Respirator, Mask, Filtration efficiency, Static electricity, Filter test

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1. Introduction

Respirators and masks represent personal protective equipment that are used to protect the wearer from airborne particles and from liquid or droplets contaminating the face (FDA). Respirators (or industrial particulate respirators) have been used to protect workers' respiratory system from environmental factors in the workplace. However, air contamination due to yellow dust and fine dust have gradually worsened, and it has become common for workers as well as all residents to wear masks (for public-use). In particular, due to the recent COVID-19 outbreak, wearing a respirator has become a necessity. As a result, the production and usage of respirators are increasing, however, the focus has been solely given on increasing the amount of production, and studies on the efficiency of masks are limited.

Respirators are subject to various regulatory standards all around the world. These regulations specify their requisite physical properties and performance characteristics (Klimek et al., 2020). The most commonly used respirator class descriptor is filtration efficiency. Almost all respirator classes used worldwide such as N95 (United States), FFP2 (European Union), KN95 (China), and 1st class respirators (Korea) have approximately 94–95% filtration efficiency. Protocols provided by the European Union (EU) and the National Institute for Occupational Safety and Health (NIOSH) are typically used worldwide (Jung., 2014). Korea also follows EU standards, and the efficiency requirements specified by the Korea's Ministry of Employment and Labor for Second, First, and Special series of respirators are the same as the European requirements for FFP1/P1, FFP2/P2, and FFP3/P3, respectively (Cho et al., 2011). The Ministry of Food and Drug Safety (MFDS, formerly known as the Korea Food & Drug Administration or KFDA) has promoted the testing criteria of mask filtration efficiencies for public use since 2014. KF-94 has a 94% filtration efficiency similar to 1st class respirators, and KF-80 has 80% efficiency similar to 2nd class respirators.

The absorption of aerosol in the respirator is caused by various mechanisms such as gravity sedimentation, inertial impaction, interception, diffusion, and electrostatic attraction. The rigidity of the respirator's filter is increased by placing a number of fibers at a certain space to obtain high efficiency and ability to filter smaller particles, however, there is a problem associated with increase in pressure drop, which makes breathing difficult. To compensate for these problems, the technique of capturing particles using electrostatic force was implemented in respirators after 1995 (Ahn., 1997; Murtadlo et al., 2019; Park., 2020). Static electricity accounts for 20% of the filtration mechanism, however, the electrostatic mechanisms work excellent for filtering finer particles that cannot be filtered by inertia, impaction, and Brownian diffusion (Chazelet et al., 2011). However, these electrostatic filters could potentially lose their static electricity and filtration efficiency when exposed to moisture for a long duration, such as exposure to exhaling breaths or storage in humid places (Sugihara, 2020). Contact with charged particles also reduces static electricity (Moyer et al., 2000).

Previous studies on masks are mostly restricted to N95. Several studies investigating the effect of static electricity on electrostatic filters have also been carried out, however, most of them were conducted with filters, and not with masks. Studies on masks have been conducted about filtration mechanism of masks, and only a few studies have attempted to evaluate the relation between change in filtering efficiency and the mechanism of filtration.

The objective of this study was to evaluate the electrostatic properties and filtration efficiency of respirators according to their increasing duration of usage, changes in temperature and humidity, and particle effects. Finally, this study aimed to correlate static electricity with filtration efficiency of respirators

2. Materials and Methods

2.1. Samples (Respirators)

In this study, four manufacturers of respirators were selected for the experiment, and the following two types of respirators from each manufacturer were tested: i) occupational-use respirators (1st class), and ii) public-use respirators (KF-94). 1st class respirators are approved by the Korean Occupational Safety and Health Agency (KOSHA), and its performance standards are considered to be equivalent to N95 or FFP2 respirators. KF-94 is approved by the Korea's Ministry of Food and Drug Safety (MFDS). The basic information of the respirators selected for this study is summarized in **Table 1**.

Table 1. Information of respirator samples.

Manufacturer	Approved class	Shape	Valve	Layers
A	1st Class	4-fold	yes	5
	KF-94	3-fold	No	5
B	1st Class	2-fold	yes	4
	KF-94	3-fold	No	4
C	1st Class	3-fold	yes	3
	KF-94	2-fold	No	3
D	1st Class	2-fold	yes	3
	KF-94	2-fold	No	3

2.2. Experimental design

Removal of electrostatic properties

To remove the electrostatic properties, the respirators were treated with isopropanol (IPA) following the electrostatic discharging protocol given by European Standard EN 779 (2012). The respirators were immersed in IPA for three minutes. After treatment with IPA, the respirators were dried for 24 h in a fume-hood.

Aging

Respirators were placed under controlled temperature of 38 ± 2.5°C and relative humidity 85 ± 5% for eight hours. These conditions reflect the temperature and humidity conditions while wearing the respirators, and the time represents the wearing period for one day. After exposing the respirators for eight hours, they were left at room temperature (20°C, 50% RH) for 16 h. This cycle was repeated for 1, 2, 4, and 8 d.

Humidity and Temperature

The influence of relative humidity and temperature on the electrostatic and filtration efficiency of respirators were studied. To evaluate the impact of humidity on the respirators, the temperature was fixed at 25°C and the RH was changed. Tests were carried out under three RH levels; 30, 50, and 98% for 24 h. To evaluate the impact of temperature on respirators, the relative humidity was fixed at 50%, and the temperature conditions were changed. Temperature conditions were changed to –30, 25, and 70℃ for 24 h.

Actual mask usage

To investigate the influence of behavior of the actually worn respirators, ten adults (five men and five women) were recruited. Respirators (KF-94) worn by participants for 1, 2, and 4 d were collected. Participants recorded the wearing duration, mechanism of storage, real-time activities, etc., while using the respirator.

2.3. Instrumentation

Filtration efficiency

Automated Filter Tester (8130A, TSI, USA) was used for evaluating the filtration efficiency and loading test. Filter tester was used with i) salt aerosol generators (8118A and 8118A-EN, TSI, USA) for sodium chloride, and with ii) oil generators (1081414R-EN, TSI, USA) for paraffin oil. The average particle size of NaCl and paraffin oil was 0.6 µm and 0.4 µm, respectively. The air flow rate was 95 l/m for all tests. The filtration efficiency test was carried out in this study following the European standard (EN-143: 2000).

TSI-8130A filter tester measures particle concentration before (upstream) and after (downstream) the test filter using a photometer, respectively. Based on the photometer output signals, the filtration efficiency of the filter can be calculated as follows:

$$P\ (\%) = \frac{C_{down}}{C_{up}} \times 100$$

C_{up} : upstream concentration

C_{down} : downstream concentration

Static electricity

The surface potential was measured to determine static electricity of respirators using electrostatic field meter (FMX-004, Simco, Japan). Sample was hung on insulation component and was placed far away from other objects. During the experiment, anti-static suit and gloves were worn to reduce the generation of static electricity. After measuring the static electricity on the outer surface of respirator, it was cut to take measurements at each layer, and eventually eight locations of each surface were measured and averaged. The measurement was performed at a temperature of 23.4℃ and RH of 42%.

2.4. Data analysis

In this study, filtration efficiency and static electricity has been expressed in terms of arithmetic mean (AM) and standard deviation (SD). The filtration efficiency and static electricity of respirator were compared using analysis of variance (ANOVA) for different periods of aging, humidity, temperature, and their actual usage period. Bonferroni method was used for post-hoc analysis. Correlation analysis was conducted to compare static electricity and filtration efficiency of respirator under each condition. Pearson and Spearman method were used for correlation analysis, whereby $r > 0.6$ was considered to be correlated, and $P < 0.05$ was considered statistically significant. Statistical analysis was performed using R software v.4.0.4. (R Development Core Team, Vienna, Austria).

3. Results

3.1. Effect of electrostatic force on filtration efficiency

Owing to the removal of static electricity from the respirator with IPA treatment, the filtration efficiency decreased by approximately 20.37 %. **Figure 1** shows a comparison of filtration efficiency before and after IPA treatment. In all respirators, the filtration efficiency after IPA treatment had significantly decreased compared to the filtration efficiency before IPA treatment ($p<0.05$). The efficiency of IPA-treated 1st class and KF-94 respirators decreased by 21.72% and 19.53%, respectively, compared to that of before the treatment. The comparison of filtration efficiency before and after treatment for each manufacturer are shown in **appendix 2**. Most of the changes were observed in respirator B (both 1st class and KF-94). Respirator B and D exhibited similar reduction rates in 1st class and KF-94, whereas the efficiency of respirator A was further decreased in 1st class, and that of C decreased in KF-94 (**appendix 2**). For pressure drop, there was no significant difference between before and after IPA treatment. Information on pressure is provided in the **appendix 3**.

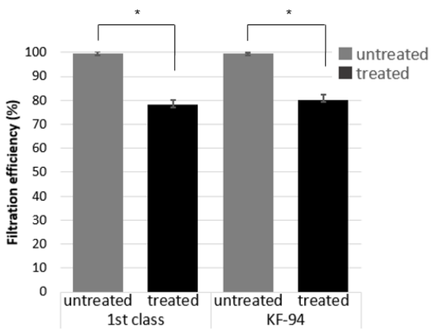


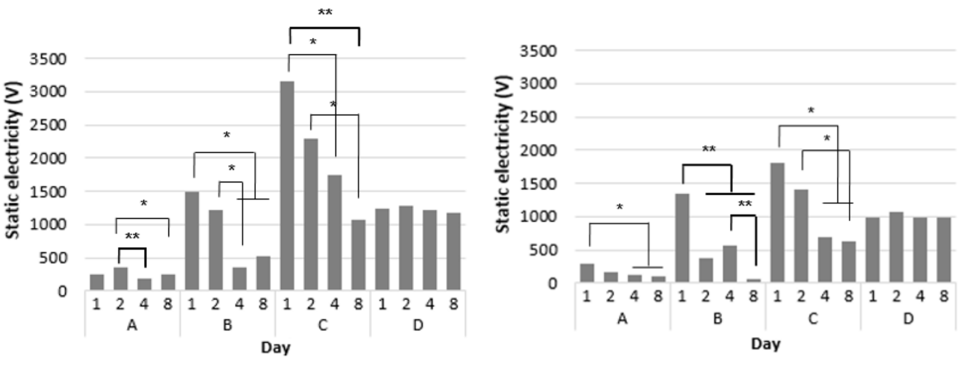
Figure 1. Filtration efficiency before and after IPA treatment. Error bars show standard deviation.

* $P<0.05$ and p values are based on pairwise comparisons using Bonferroni method.

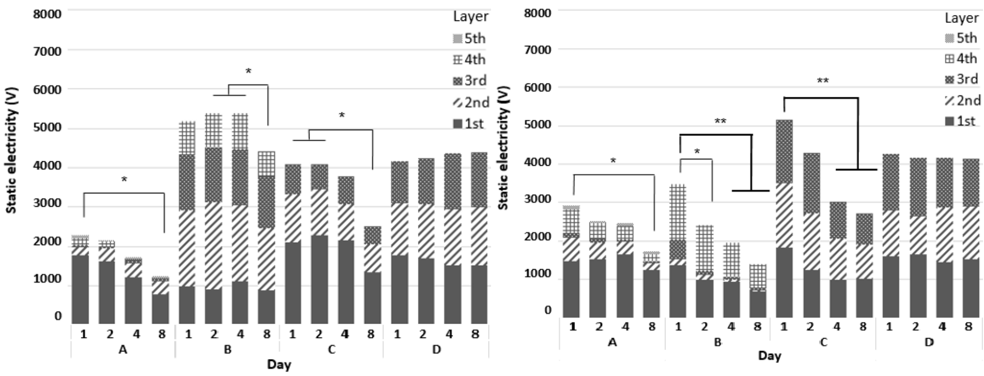
3.2. Effect of aging on static electricity and filtration efficiency

Static electricity

The variation in the static electricity of respirators over time (1, 2, 4, and 8 d) on the outer surface of respirators (before cutting) is shown in **Fig 2(a–b),** and that in individual layers of respirators is displayed in **Fig 2(c–d)**. The static electricity of respirators differed significantly according to time ($p<0.05$), except for one manufacturer D. After eight days, the static electricity was significantly decreased compared to that after one day. For manufacturer B, the static electricity of the surface (before cutting) was decreased by 65.37%, and the total static electricity of individual layers was decreased by 17.58% in 1st class respirators. The static electricity of the surface was decreased by 96.31% and the total static electricity of each layer was decreased by 59.68% in KF-94. For manufacturer C, the static electricity of the surface was decreased by 65.78 and 65.56%, and the total static electricity of each layer was decreased by 38.46 and 47.15% in 1st class and KF-94, respectively.



(a) Outer surface electricity of 1st class **(b) Outer surface electricity of KF-94**



(c) Surface electricity in individual layers of 1st class

(d) Surface electricity in individual layers of KF-94

Figure 2. Variation in static electricity over time.

* P<0.05, ** P<0.001 and p values are based on pairwise comparisons using Bonferroni method.

Filtration efficiency

The filtration efficiency of respirators generally decreased over time, however, no significant differences, except for a few samples, were observed (**Table 2**). Only one KF-94 (manufacturer B) displayed sharp decrease in filtration efficiency over time while using each NaCl and paraffin oil (p<0.001). The filtration efficiency was 99.93 ± 0.00 and 99.23 ± 0.66% on day 1 (after 8 h), but decreased to 93.44 ± 1.08 and 91.12 ± 1.09% after 8 d in NaCl and paraffin oil, respectively. Thus, the filtration efficiency was below 94%, which is considered the standard for filtration efficiency test. KF-94 (A) displayed significant differences in terms of filtration in NaCl, and another respirator, 1st class (B), had significant differences in terms of filtration efficiency in paraffin oil (p<0.05). Overall, the filtration efficiency did not alter significantly with time for 1st class, although it differed significantly for KF-94 (<0.05)

The pressure drop of respirator by manufacturer B (both 1st class and KF-94) differed significantly with time (p<0.05). The pressure drop of 1st class (B) was significantly increased over time, and that of KF-94 (B) had decreased over time. Another 1st class respirator (A) also displayed significant alteration with time, whereby pressure drop increased from 2 to 8 d (except for day 1). Information on changes in pressure is provided in the **appendix 4**.

Table 2. Filtration efficiency over time for (a) NaCl, and (b) Paraffin oil

(a) NaCl

Day			1	2	4	8	**P-value**
Manufacturer	Class	N	(Mean ± SD)	(Mean ± SD)	(Mean ± SD)	(Mean ± SD)	
A	1st Class	5	99.81±0.17	99.74±0.12	99.75±0.12	98.50±1.75	0.347
	KF-94	5	99.89±0.01	99.82±0.06	99.83±0.05	98.87±0.61	**0.010**
B	1st Class	5	99.85±0.13	99.86±0.07	99.54±0.49	99.24±0.65	0.291
	KF-94	5	99.93±0.00	99.67±0.31	98.68±1.27	93.44±1.08	**<0.001**
C	1st Class	5	99.70±0.22	99.78±0.20	99.78±0.17	98.97±1.14	0.390
	KF-94	5	99.15±0.24	99.22±0.40	99.12±0.12	98.68±0.50	0.342
D	1st Class	5	99.82±0.13	99.90±0.03	99.90±0.03	99.83±0.06	0.358
	KF-94	5	99.80±0.08	99.74±0.09	99.54±0.48	98.93±1.42	0.589
Total	1st Class	20	99.64±0.37	99.51±0.97	99.74±0.27	99.60±0.62	0.849
	KF-94	20	99.67±0.34	99.61±0.38	99.03±0.98	97.79±2.70	**0.010**

Filtration efficiency (%)

(b) Paraffin oil

Day			1	2	4	8	**P-value**
Manufacturer	Class	N	(Mean ± SD)	(Mean ± SD)	(Mean ± SD)	(Mean ± SD)	
A	1st Class	5	99.50±0.13	99.39±0.41	99.10±0.34	99.01±0.20	0.226
	KF-94	5	99.65±0.12	99.43±0.55	99.40±0.28	99.26±0.52	0.736
B	1st Class	5	99.90±0.02	99.82±0.07	99.76±0.06	99.44±0.19	**0.004**
	KF-94	5	99.23±0.66	99.35±0.64	98.45±1.08	91.12±1.09	**3.45E-05**
C	1st Class	5	99.53±0.36	99.72±0.34	98.95±1.08	98.97±0.69	0.419
	KF-94	5	97.71±0.15	97.82±0.12	97.38±0.10	96.95±0.69	0.099
D	1st Class	5	99.69±0.16	99.65±0.12	99.59±0.15	99.32±0.13	0.107
	KF-94	5	99.49±0.10	99.38±0.42	99.25±0.35	99.15±0.34	0.727
Total	1st Class	20	99.35±0.27	99.55±0.37	99.48±0.59	99.46±0.49	0.803
	KF-94	20	98.87±0.97	98.89±0.76	98.79±0.95	96.69±3.56	**0.028**

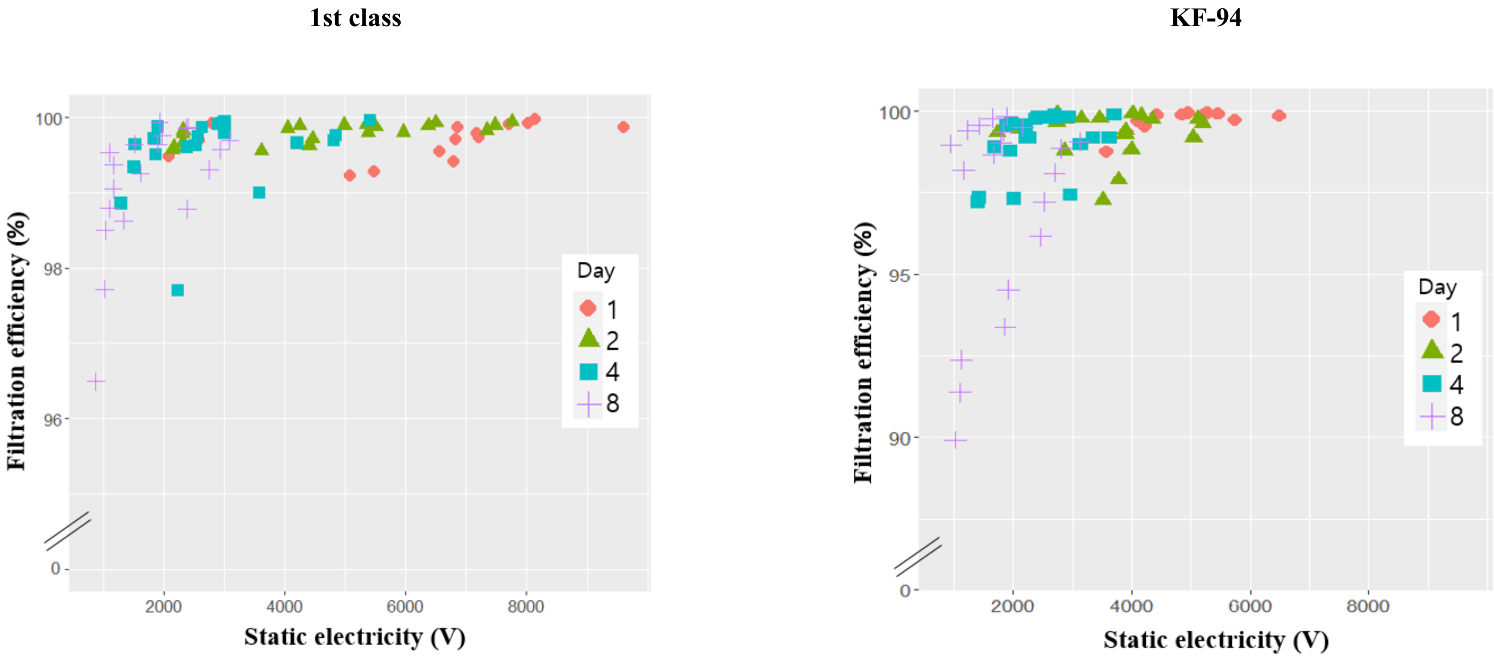
Filtration efficiency (%)

* P<0.05 and p values are based on ANOVA analysis (among 1, 2, 4, and 8 d)

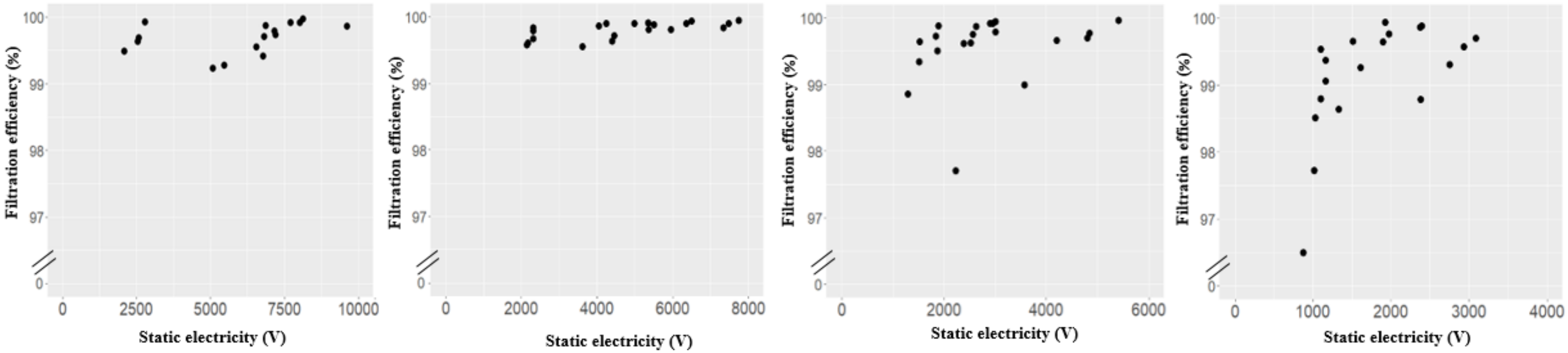
Correlation between static electricity and filtration efficiency

Figure 3 illustrates the correlation between static electricity and filtration efficiency over time. The correlation analysis indicated that the r values were 0.4306 and 0.2462 for 1st class and KF-94, respectively, and all correlations were statistically significant ($p<0.05$) (**Fig 3a**). There was generally no correlation in KF-94 with respect to wearing duration, however, in 1st class, positive correlations were observed on the 2^{nd} and 4^{th} days (r =0.6704 and 0.6526, respectively) (**Fig 3(b–c)**). In terms of KF-94, respirators from manufacturer B and C showed positive correlations on day 8, however, there was no correlation between static electricity and filtration efficiency in respirators from manufacturer A and D (**Fig 3c**). Overall, there was minor correlation over time, and 1st class displayed stronger correlation compared to KF-94.

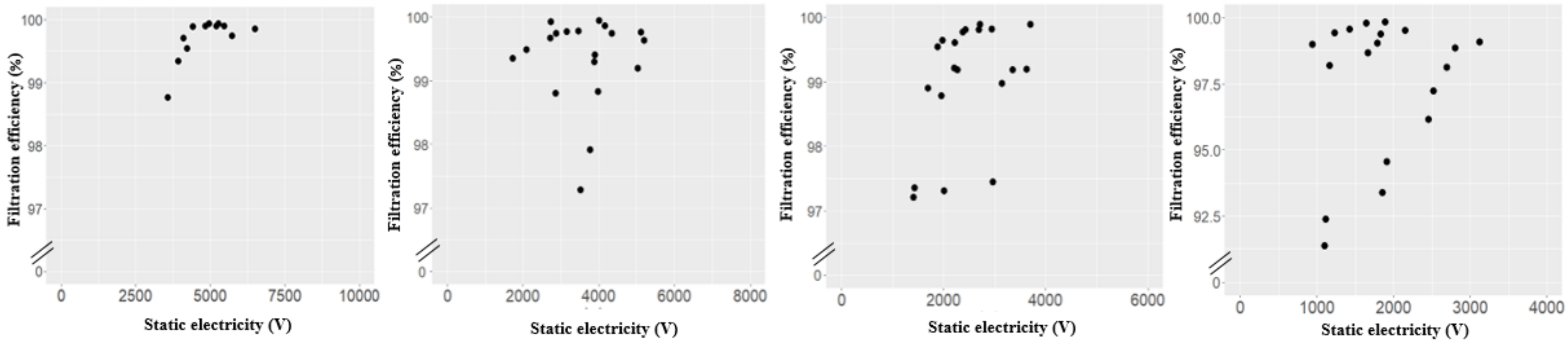
(a)


1st class
KF-94
Filtration efficiency (%)
100
98
96
0
2000
4000
6000
8000
Static electricity (V)
Day
1
2
4
8
Filtration efficiency (%)
100
95
90
0
2000
4000
6000
8000
Static electricity (V)
Day
1
2
4
8

(b) 1st class



(c) KF-94



1 day **2 days** **4 days** **8 days**

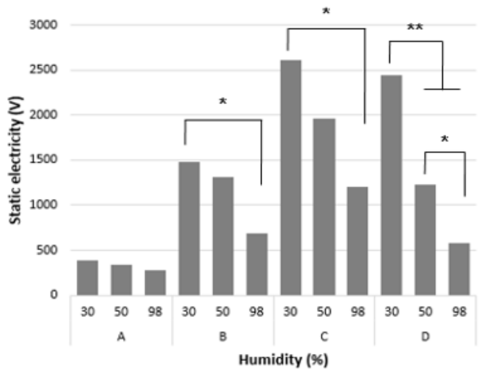
Figure 3. Correlation between static electricity and filtration efficiency over time. (a) correlation for several days shown in one plot (r =0.4306, 0.2462), and (b–c) correlation on different days ((b) r =0.3651, 0.6704, 0.5137, 0.6526; (c) r =-0.2029, 0.0860, 0.488, 0.3438).

3.3. Effect of humidity and temperature on static electricity and filtration efficiency

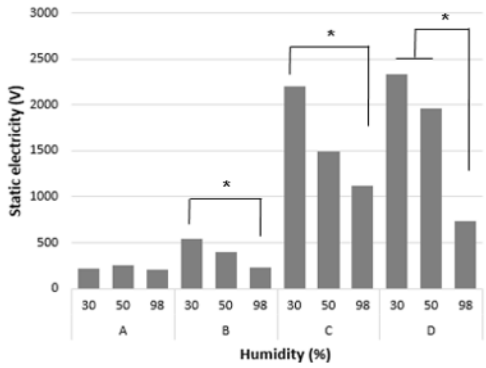
Static electricity

Figure 4 shows the static electricity of respirators at different relative humidity (RH) of 30, 50, and 98%**.** The static electricity tended to decrease with increase in humidity. At high humidity (98% RH), the static electricity displayed a sharp decrease. The static electricity on the outer surface of respirators differed significantly with respect to RH ($p<0.05$) except for manufacturer A (both 1st class and KF-94) (**Fig 4(a–b)**). The total static electricity of individual layers differed significantly according to RH ($p<0.05$) except for one manufacturer B in 1st class and A in KF-94 (**Fig 4(c–d)**). In case of respirator A, the static electricity of the fourth layer decreased according to humidity, and in case of respirator B, the decrease was evinced in second and third layers. In case of respirators C and D, electrostatic reduction was shown in all layers.

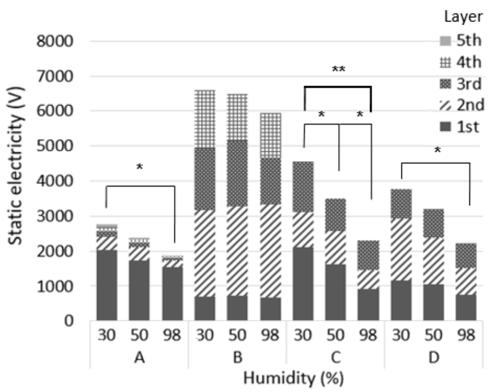
Figure 5. shows static electricity of respirators at difference temperature (–30, 50, and 70°C). There was no significant difference in static electricity with respect to temperature except for one 1st class respirator (manufacturer A). Only respirator A showed significant decrease in static electricity at high temperature (70°C).



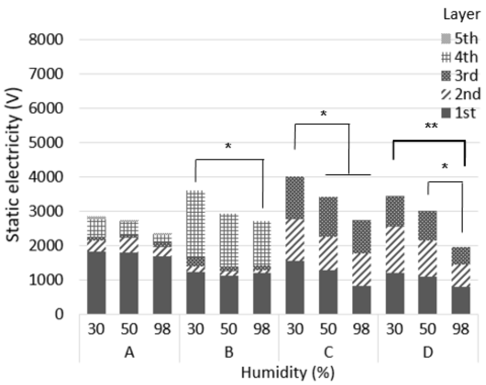
(a) Outer surface electricity of 1st class



(b) Outer surface electricity of KF-94



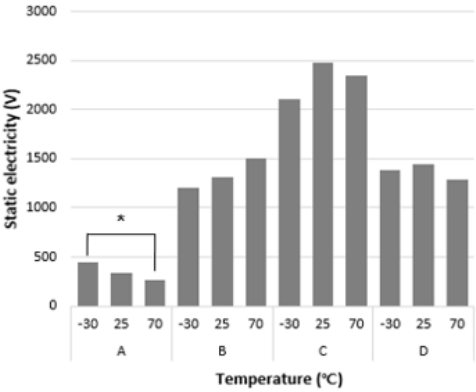
(c) Electricity of 1st class at individual layers



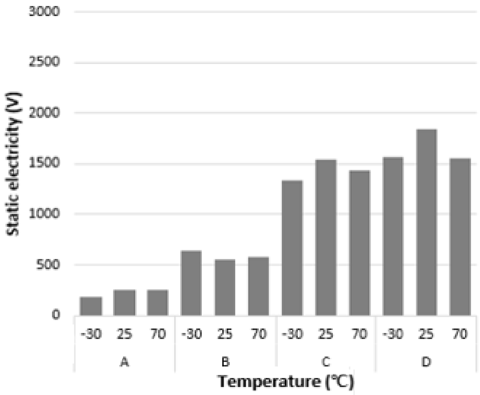
(d) Electricity of KF-94 at individual layers

Figure 4. Static electricity at different relative humidities (RH).

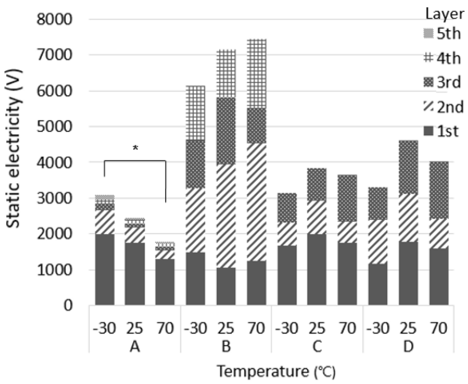
* P<0.05, ** P<0.001 and p values are based on pairwise comparisons using Bonferroni method.



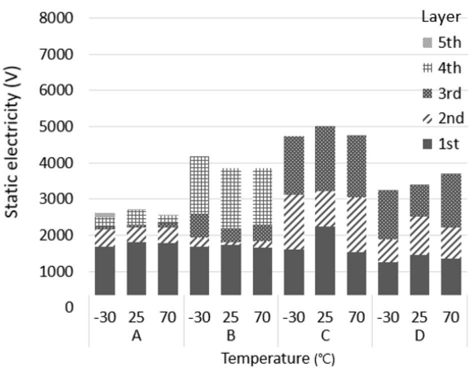
(a) Outer surface electricity of 1st class



(b) Outer surface electricity of KF-94



(c) Electricity of 1st class at each later



(d) Electricity of KF-94 at each later

Figure 5. Static electricity at different temperatures.

* P<0.05, ** P<0.001 and p values are based on pairwise comparisons using Bonferroni method.

Filtration efficiency

The filtration efficiency of respirators at different relative humidity (30, 50, and 98%) is provided in **Table 3**. Two 1st class (A and B) and two KF-94 (C and D) respirators exhibited significant differences in filtration efficiency according to RH (P<0.05) in both NaCl and paraffin oil medium. Manufacturer B (both 1st class and KF-94) showed a significant difference in filtration efficiency with paraffin oil, and the efficiency of one 1st class (D) respirator displayed significant variation with RH in NaCl. Overall, the filtration efficiency displayed significant variations with humidity in 1st class ($p<0.05$) and KF-94 respirators (<0.001). At high humidity (98% RH), the filtration efficiency decreased to 98.53±2.27 and 98.63±1.04 % for 1st class and KF-94, respectively, in NaCl medium. On the other hand, the two respirator classes displayed decreased efficiency at 98.91±0.59 and 98.24±0.85% for 1st class and KF-94, respectively, in paraffin oil.

The filtration efficiency of respirators at different temperature (–30, 25, and 70°C) is given in **Table 4**. There was no difference in filtration efficiency with respect to temperature except for a few samples. One KF-94 (D) respirator showed significant difference in filtration efficiency for 1st class and paraffin oil, and another KF-94 (C) had a significant difference in filtration efficiency for paraffin oil ($p<0.05$). Overall, the filtration efficiency did not significantly differ according to temperature, unlike RH.

The pressure drop of 1st class (A) was decreased at high humidity (98% RH) ($p<0.05$). The pressure of manufacturer A and B was low at low temperature (–30°C), and pressure of manufacturer C and D was low at high temperature (70°C). Information on pressure is provided in the **appendix 7–8**.

Table 3. Filtration efficiency at different relative humidities (RH)

RH (%)			30		50		98		P-value*	
			Filtration efficiency (%)		Filtration efficiency (%)		Filtration efficiency (%)		Filtration efficiency	
Manufacturer	Class	N	NaCl (Mean ± SD)	Paraffin Oil (Mean ± SD)	NaCl (Mean ± SD)	Paraffin Oil (Mean ± SD)	NaCl (Mean ± SD)	Paraffin Oil (Mean ± SD)	NaCl	Paraffin Oil
A	1st Class	5	99.87±0.05	99.73±0.04	99.64±0.03	99.46±0.29	99.22±0.17	99.08±0.25	**<0.001**	**0.020**
	KF-94	5	99.66±0.25	99.45±0.08	99.68±0.06	99.59±0.03	98.72±0.93	98.41±1.38	0.128	0.231
B	1st Class	5	99.96±0.01	99.90±0.04	99.92±0.01	99.84±0.06	97.85±4.09	98.99±0.79	0.521	**0.034**
	KF-94	5	99.62±0.16	99.83±0.10	99.65±0.17	99.66±0.17	98.58±1.54	98.51±0.55	0.266	**0.004**
C	1st Class	5	99.66±0.35	99.84±0.15	99.12±0.08	99.73±0.15	98.72±0.26	98.92±0.68	**0.004**	**0.023**
	KF-94	5	99.28±0.14	98.77±0.22	99.08±0.73	98.07±0.22	98.00±0.91	97.52±0.19	**0.026**	**<0.001**
D	1st Class	5	99.69±0.82	99.64±0.06	99.68±0.23	99.49±0.16	98.58±0.65	98.59±0.79	**0.048**	0.119
	KF-94	5	99.81±0.22	99.43±0.16	99.71±0.10	99.17±0.09	99.39±0.18	98.83±0.20	**0.005**	**0.010**
Total	1st Class	20	99.80±0.22	99.80±0.13	99.55±0.34	99.65±0.23	98.53±2.27	98.91±0.59	**0.049**	**<0.001**
	KF-94	20	99.57±0.25	99.43±0.44	99.55±0.27	99.04±0.72	98.63±1.04	98.24±0.85	**<0.001**	**<0.001**

* P<0.05 and p values are based on ANOVA analysis (among 30, 50, and 98%)

Table 4. Filtration efficiency at different temperatures

Temperature (℃)			–30		25		70		P-value*	
Manufacturer	Class	N	Filtration efficiency (%)		Filtration efficiency (%)		Filtration efficiency (%)		Filtration efficiency	
			NaCl (Mean ± SD)	Paraffin Oil (Mean ± SD)	NaCl (Mean ± SD)	Paraffin Oil (Mean ± SD)	NaCl (Mean ± SD)	Paraffin Oil (Mean ± SD)	NaCl	Paraffin Oil
A	1st Class	5	99.52±0.13	99.47±0.27	99.64±0.03	99.46±0.29	99.43±0.15	99.12±0.48	0.171	0.510
	KF-94	5	99.21±1.02	99.26±0.56	99.68±0.06	99.59±0.03	99.57±0.23	99.42±0.13	0.578	0.448
B	1st Class	5	96.78±3.00	99.63±0.06	99.92±0.01	99.84±0.06	99.57±0.02	99.71±0.16	0.126	0.113
	KF-94	5	99.22±0.97	99.80±0.07	99.65±0.17	99.66±0.17	99.85±0.07	99.64±0.06	0.315	0.353
C	1st Class	5	99.89±0.04	98.71±1.73	99.12±0.08	99.73±0.15	99.42±0.56	99.22±0.73	0.089	0.461
	KF-94	5	99.17±0.29	96.52±1.09	99.08±0.73	98.07±0.22	99.17±0.14	97.22±0.46	0.793	**0.039**
D	1st Class	5	99.88±0.10	99.58±0.31	99.68±0.23	99.49±0.16	99.33±0.48	99.10±0.23	0.271	0.112
	KF-94	5	99.80±0.09	97.87±0.25	99.71±0.10	99.17±0.09	99.44±0.13	98.23±0.39	**0.020**	**0.007**
Total	1st Class	20	98.77±2.12	99.28±0.97	99.55±0.34	99.65±0.23	99.43±0.33	99.29±0.47	0.249	0.197
	KF-94	20	99.35±0.61	98.36±1.44	99.55±0.27	99.04±0.72	99.50±0.29	98.63±1.05	0.477	0.339

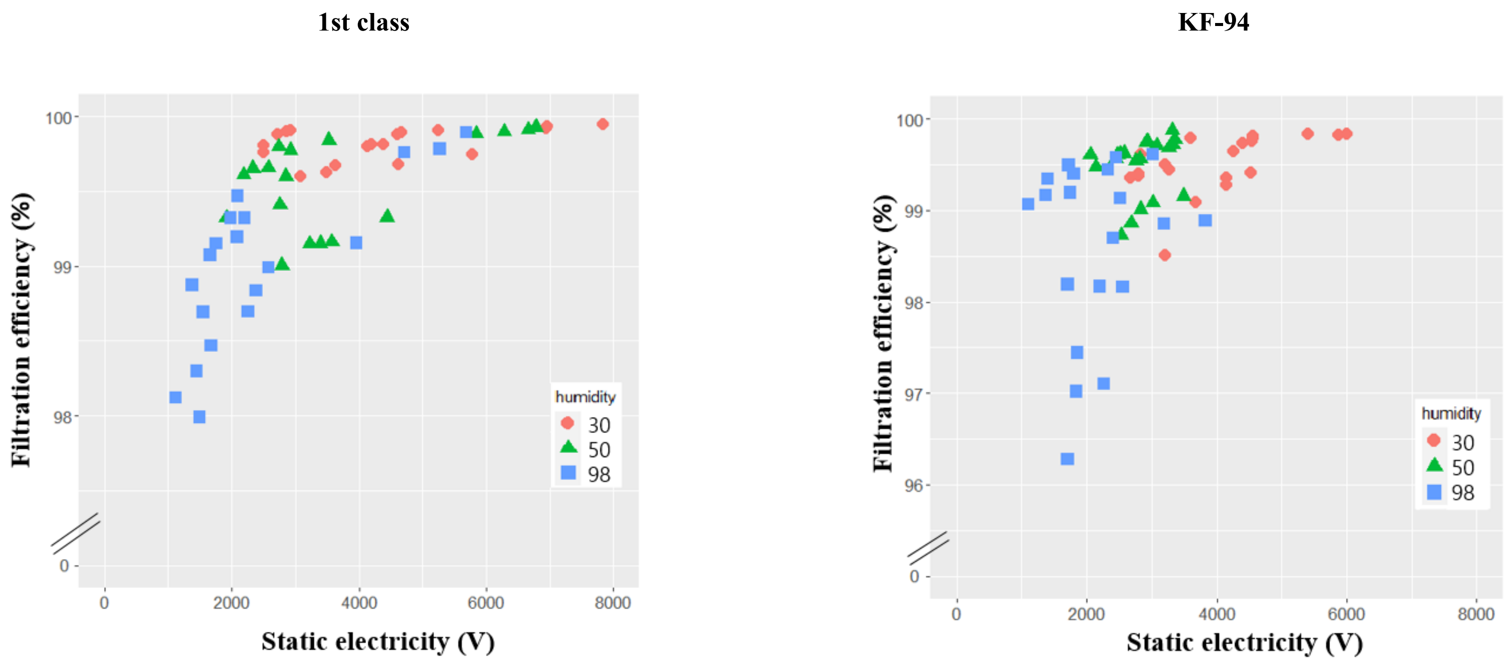
* $P<0.05$ and p values are based on ANOVA analysis (–30, 25, and 70℃)

Correlation between static electricity and filtration efficiency

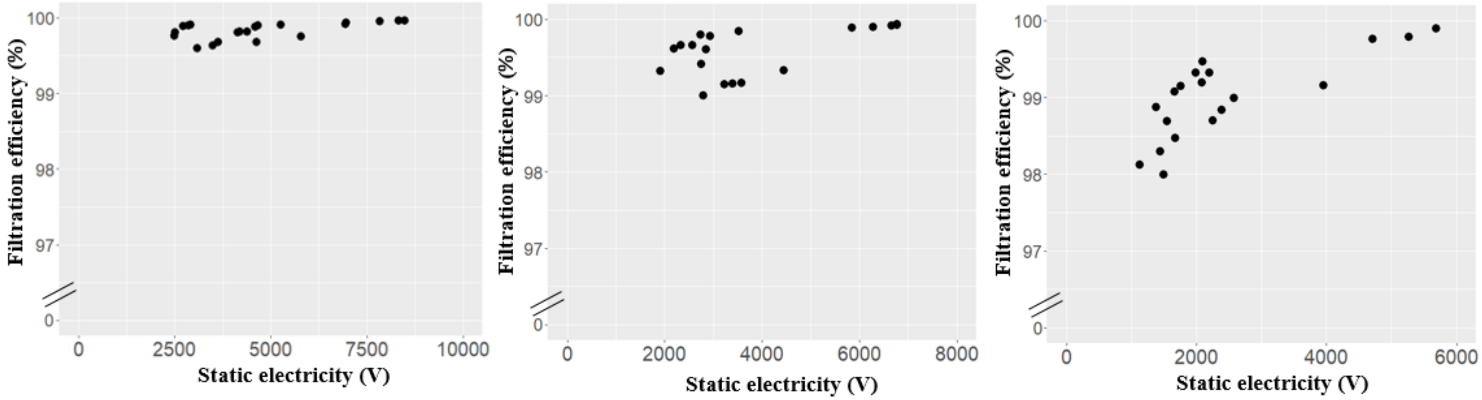
Figure 6 shows correlation between static electricity and filtration efficiency with respect to relative humidity, which is positive in both 1st class and KF-94 with r =0.7753 and 0.5591, respectively (**Fig 6a**). For 1st class, the filtration efficiency did not decrease at 30 and 50% RH, therefore, no correlation was observed. At high humidity (98% RH), the filtration efficiency of KF-94 decreased, however, the static electricity did not significantly decrease (**Fig 6(b–c)**).

Figure 7 shows correlation between static electricity and filtration efficiency with respect to temperature, the r values of which were 0.3384 and 0.3364 for 1st class and KF-94, respectively (**Fig 7a**). The filtration efficiency of respirators decreased with the decrease in static electricity at low (–30°C) and high (50°C) temperatures (**Fig 7(b–c)**). Overall, 1st class showed a slightly stronger correlation than KF-94.

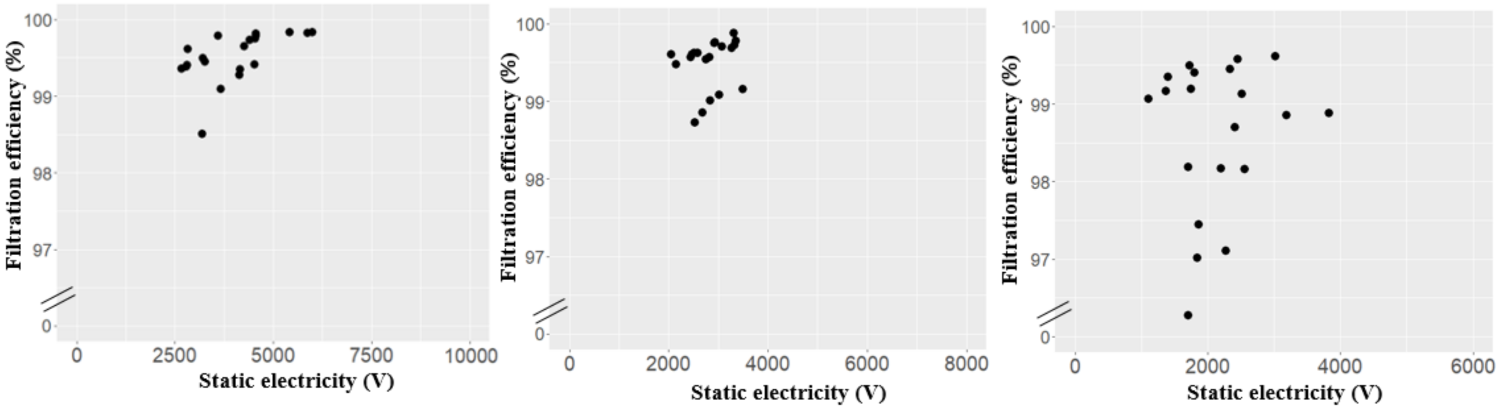
(a)


1st class
KF-94
Filtration efficiency (%)
Static electricity (V)
humidity
30
50
98
100
99
98
97
96
0
2000
4000
6000
8000

(b) 1st class



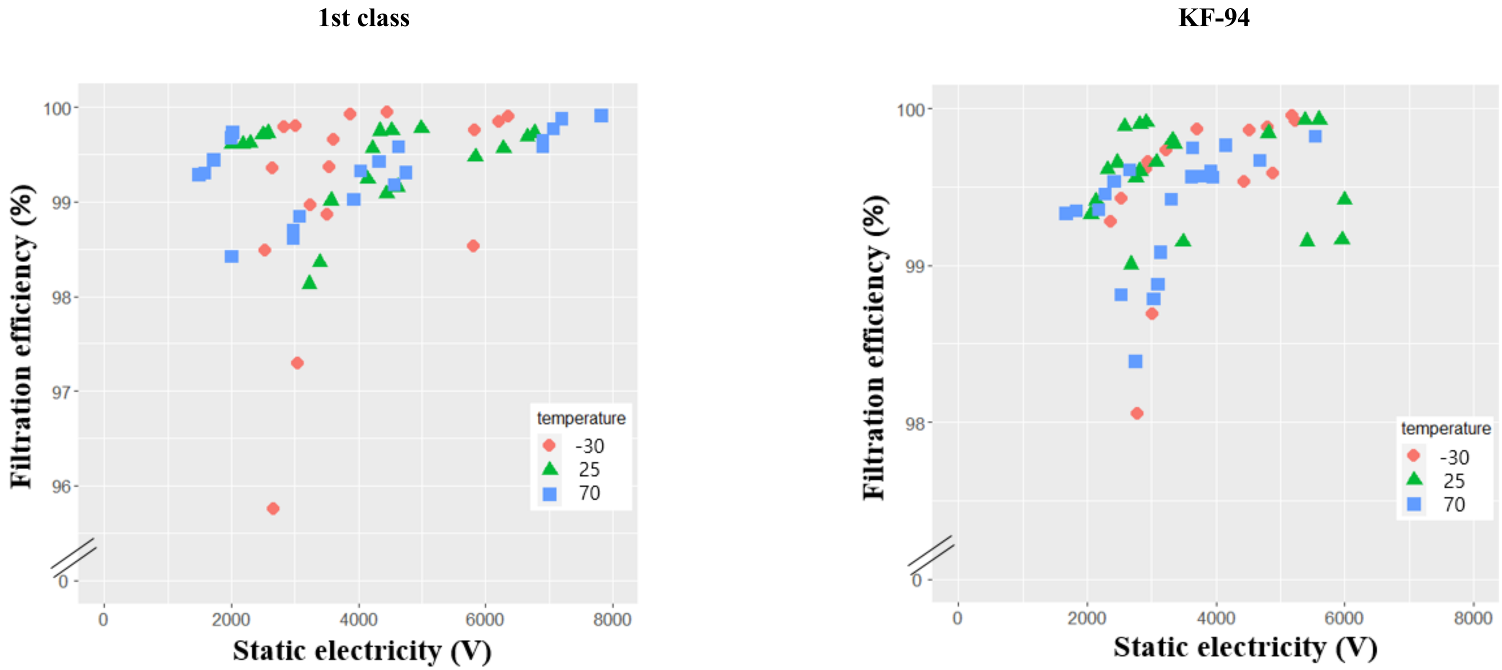
(c) KF-94



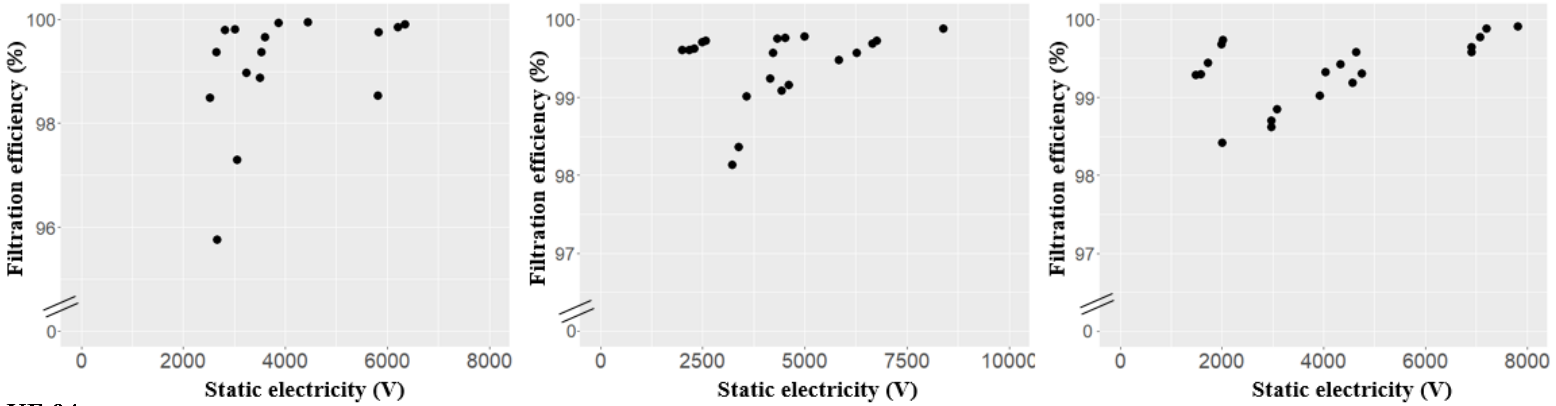
30 % **50 %** **98 %**

Figure 6. Correlation between static electricity and filtration efficiency with respect to relative humidity. (a) correlation for several RH conditions shown in one plot (r =0.7753, 0.5591), and (b–c) correlation at individual RH conditions ((b) r =0.5488, 0.5175, 0.5895; (c) r =0.5496, 0.4045, 0.1252).

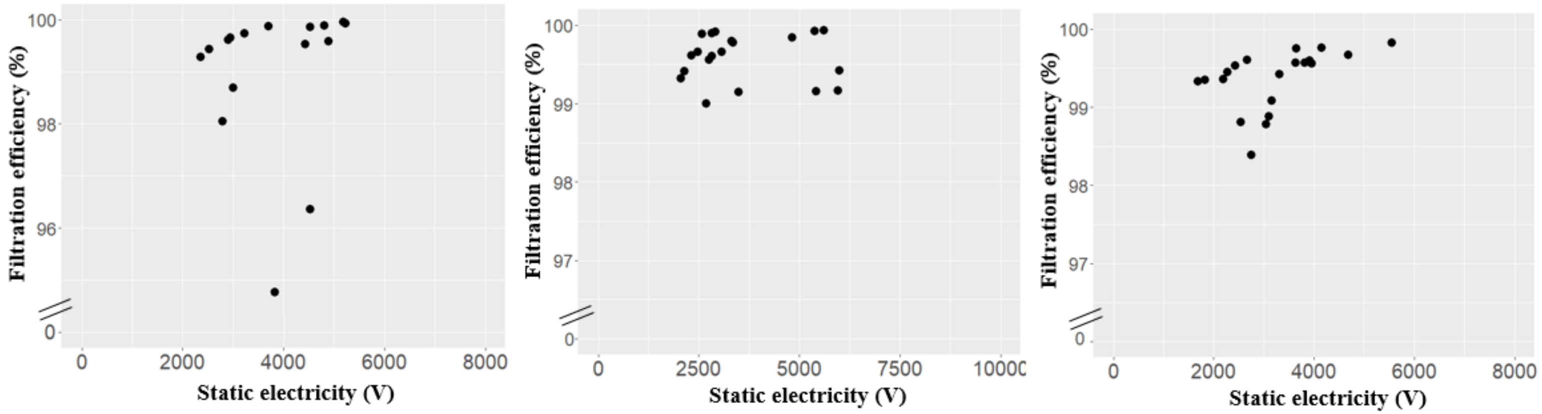
(a)


1st class
KF-94
Filtration efficiency (%)
Static electricity (V)
100
99
98
97
96
0
2000
4000
6000
8000
temperature
-30
25
70

(b) 1st class



(c) KF-94



–30 ℃ 25 ℃ 70 ℃

Figure 7. Correlation between static electricity and filtration efficiency with respect to temperature. (a) correlation for several temperature conditions shown in one plot (r =0.3384, 0.3364), and (b–c) correlation at individual temperature conditions ((b) r =0.5647, 0.2782, 0.5371; (c) r =0.5, 0.1234, 0.6511).

3.4. Variation of static electricity and filtration efficiency according to mask-wearing duration

Static electricity

Figure 8 shows the static electricity of masks that were actually worn by the participants. The static electricity was decreased according to the mask-wearing duration. The static electricity on the surface was 751.72, 499.51, and 268.6 V. The total static electricity of each layer was 2485.47, 2389.66, and 2205.62 V on the 1st, 2nd and 4th days, respectively. The static electricity of the mask worn for four days was significantly lower than new masks or those worn for only one day ($p<0.05$).

(a) **(b)**

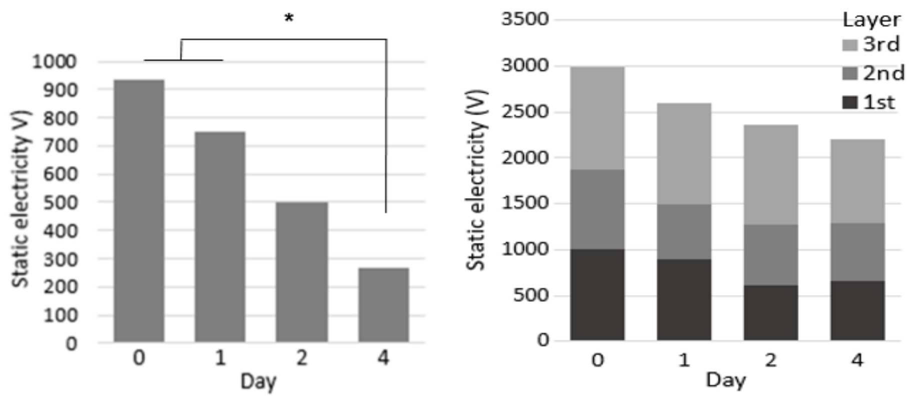


Figure 8. Static electricity (a) on the outer surface of respirators, and (b) for individual layer of respirators at different mask-wearing durations.

* P<0.05 and p values are based on pairwise comparisons using Bonferroni method.

Filtration efficiency

Table 5 shows the filtration efficiency and pressure drop of the actually worn masks. Day 0 represents the measurements taken immediately after the respirator was taken out of the package. Masks were collected from eight participants (four men and four women) for different wearing durations. The maximum efficiency was 99.79, 99.66, and 98.23 %, and the minimum was 92.4, 80.82, and 82.27 % for the 1st, 2nd, and 4th days. The filtration efficiency decreased, and the pressure drop also decreased as the wearing duration increased. Masks worn for four days presented a significantly decreased filtration efficiency as compared to new masks or those worn for only one day ($p<0.05$).

Table 5. The filtration efficiency of the actual mask wear

Wearing duration (day)	N	Filtration efficiency (%) (Mean ± SD)	Max	Min	Pressure drop (mmH_2O) (Mean ± SD)
0*	5	99.60 ± 0.26	99.86	99.44	11.27 ± 0.77
1	8	97.91 ± 2.56	99.79	92.40	10.76 ± 0.63
2	8	95.26 ± 6.47	99.66	80.82	10.32 ± 0.72
4	8	93.11 ± 4.98	98.23	82.27	10.11 ± 0.57

* 0 day was measured immediately after the mask was taken out of the package.

Correlation between static electricity and filtration efficiency

Figure 9 illustrates the correlation between static electricity and filtration efficiency according to the mask-wearing duration. The static electricity and filtration efficiency of the actually worn masks showed a positive correlation with wearing durations. The filtration efficiency of the used masks decreased as the static electricity decreased. The r value was 0.7145, and it was statistically significant ($p<0.05$).

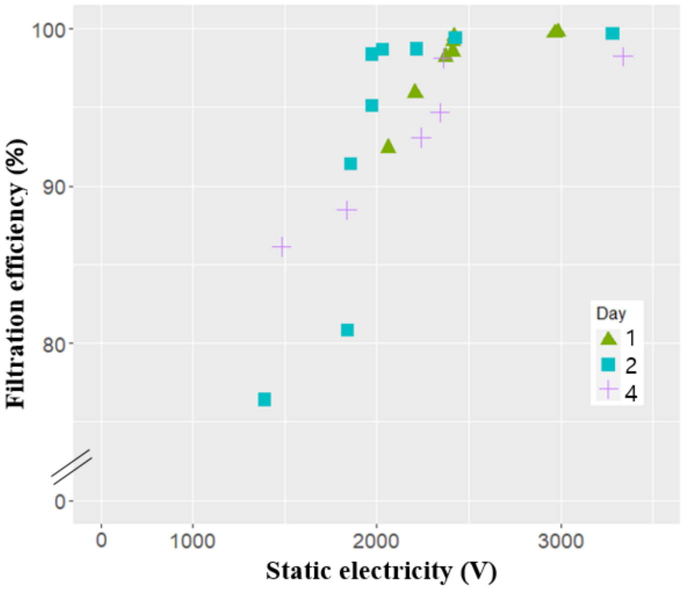


Figure 9. Correlation between static electricity and filtration efficiency according to the mask-wearing duration (r =0.7145).

4. Discussion

In this study, variations in static electricity and filtration efficiency of respirators with respect to time, humidity, and temperature were confirmed, and the correlation between them was studied. Comparison of results of 1st class and KF-94 was also conducted.

At first, static electricity was removed from the respirators, and the filtration efficiency before and after the removal of static electricity was compared. Previous studies have established that filtration efficiency decreases with decrease in static electricity, i.e., higher static electricity increases filtration efficiency (Murtadlo et al., 2019; Hwang et al., 2014; Kim et al., 2009). Kim et al. (2009) reported that upon exposing electrostatic filters to IPA, the static electricity and filtration efficiency of the electrostatic filters were reduced. On the other hand, Murtadlo et al. (2019) showed that filtration efficiency increases with increased static electricity of electric filter charged with high voltage. Sugihara (2020) compared masks that had lost static electricity after sterilization process with masks recharged with static electricity. The study indicated that the filtration efficiency of 1st class and KF-94 respirators decreased by 21.72% and 19.53%, respectively, after removal of static electricity compared to the efficiency before the removal of static electricity. It was found that static electricity contributes approximately 20.37% to the changes in filtration efficiency of respirator. It can be seen that the static electricity contributes slightly more to the changes in filtration efficiency of 1st class than KF-94.

The static electricity decreased over time in three manufacturers (A, B, and C). The filtration efficiency over time differed significantly in KF-94, and not in 1st class. For manufacturer B, the filtration efficiency of respirator decreased significantly over time. It displayed a sharp decrease after eight days. A comparison of the filtration efficiency before and after the removal of static electricity from the respirators suggested that the efficiency decrease was the highest in manufacturer B (27.09%). The trend suggests that the decrease in filtration efficiency of respirator of manufacturer B over time was associated with decrease in static electricity. Correlation analysis indicated that the filtration efficiency decreased because the static electricity had significantly decreased on day 8. The correlations displayed by 1st class respirators were higher than KF-94. For KF-94, although, the filtration efficiency decreased as the static electricity decreased in two respirators (manufacturer B and C) on day 8, the other two respirators (manufacturer A and D) did not display any significant alterations in filtration efficiency.

With respect to variations in humidity, both static electricity and filtration efficiency of 1st Class and KF-94 respirators had decreased. In particular, it decreased sharply at high humidity (98% RH). It is known that static electricity decreases with humidity (Lee and, 2020; Sugihara, 2020). This decrease in filtration efficiency might be due to a reduction in static electricity caused by humidity. Thus, this study demonstrated a positive correlation between static electricity and filtration efficiency with respect to humidity. It can be deduced that the reduction in static electricity contributes to the decrease in filtration efficiency as humidity increases.

The change of static electricity according to temperature was observed only in one 1st class (manufacturer A) respirator. However, there was no significant difference in filtration efficiency for 1st class respirators of manufacturer A, and the differences was evinced in respirators from manufacturer C and D. For manufacturer C and D, the pressure drop decreased at high temperature (70 ℃). This can be explained by other mechanical filtration mechanisms because of changes in the properties of respirator rather than due to static electricity. Although the filtration efficiency decreased according to humidity, the filtration efficiencies of all samples at different humidity and temperature were more than 94%, which is the filtration efficiency test standard, indicating that wearing these respirators does not cause any major problem.

In the real mask-wearing scenario, static electricity and filtration efficiency decreased according to the mask-wearing duration. Three respirators on day 2 and four on day 4 displayed decrease in filtration efficiency below 94%. On day 2, two participants, who wore respirators with reduced efficiency (76.42, 80.82 %), had worn it for longer hours of the day. Participants made announcements while wearing the respirator, and had placed it in a humid place when the respirator was not in use. One participant, who wore low efficiency respirator for four days, was a smoker and did intense exercise.

As the duration of wearing masks increased, the filtration efficiency decreased and the pressure drop also decreased. Since the filtration efficiency decreased despite filter clogging, the penetration of small particles seems to have increased due to decrease in static electricity. In this study, filtration efficiency was tested with particles size of 0.4 μm, the size at which other mechanical filtration mechanisms became vulnerable. Therefore, electrostatic contribution in reducing filtration efficiency appears significant. The result of correlation analysis between static electricity and filtration efficiency also demonstrated a positive correlation ($r = 0.7145$).

Most of the masks used in this study were made of polypropylene. The exterior and lining were nonwoven fabrics, and the inner filters were made of intertwined fibers. In terms of electric filters, static electricity was applied to the fibers inside the filters during the manufacturing process (Ahn, 1997; Boelter and Davidson, 1997; Grass et al., 2004). Since direct measurement of the unit length charge of the fiber was difficult, the surface potential of the filter, which is proportional to the unit length charge. was measured in this study and was used as an indicator of the strength of electrical forces in the electric filter. However, measuring the surface of the filter might not represent the entire static electricity of the inner fibers. Therefore, it was used as a relative value rather than an absolute electrostatic value. Electrostatic values were also found in other non-woven fabrics in this study. This is because electricity in the fibers inside the filter might be discharged to other attached filters or nonwoven fabrics. The static electricity from the fibers inside the filter could have been emitted over time. It is important not to lose this static electricity and preserve it well. This is an area that needs to be continuously studied in the future.

5. Conclusion

This study evaluated the changes in static electricity and filtration efficiency of respirators according to time, humidity, temperature, and mask-wearing duration. We also studied the correlation between these parameters. In addition, the results of 1st class respirators (used for occupational purposes) and KF-94 respirators (used by public) were compared.

Testing the filtration efficiency of respirators treated with IPA to remove static electricity suggested that the filtration efficiency of 1st class and KF-94 were 21.72 and 19.53% lower after the removal of static electricity compared to the filtration efficiency of respirators before electrostatic removal. The static electricity generally decreased with increasing time, however, the filtration efficiency did not vary significantly except for one. Static electricity generally decreased with time, however, there was no significant difference in filtration efficiency except for one. Since the new unworn mask has higher static electricity, a slight decrease does not the filtration efficiency below 94%. Only one KF-94 (manufacturer B) displayed sharp decrease in filtration efficiency after eight days (below 94%), which was because of decrease in static electricity. The static electricity and filtration efficiency of respirators were decreased in both 1st class and KF-94 according to humidity, however, there was no significant difference depending on temperature. In terms of actual mask-wearing scenario, the static electricity and filtration efficiency decreased as the wearing duration increased. However, the pressure drop also decreased over time. Thus, a decrease in filtration efficiency was associated with decrease in static electricity caused by humidity.

Overall, static electricity and filtration efficiency orderly decreased with increasing humidity, time, and temperature. The correlation was also strong in the same order, i.e., humidity > time > temperature. 1st class had a stronger correlation between static electricity and filtration efficiency than KF-94. It was found that the static electricity contributed more in 1st class respirators for enhancing filter efficiency.

It will be useful to refer to these results while testing masks in the future. In addition, technological developments are required to maintain static electricity in filter.

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국문초록

산업용 및 보건용 마스크의 정전기와 여과효율의 상관성에 관한 연구

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서론 마스크(호흡보호구)는 작업장에서 유해인자로부터 근로자의 호흡기를 보호하기 위해 사용되어왔으나, 황사나 미세먼지 등 일상의 환경적 요인이 악화되면서 작업자들뿐만 아니라 일반 시민들도 마스크를 착용하는 것이 보편화되었다. 마스크의 여과기전은 중력침강, 관성충돌, 차단, 확산 그리고 정전기가 있다. 고효율의 섬유필터를 얻기 위해 섬유를 일정한 공간에 많이 넣어 촘촘하게 만들어야 한다. 하지만 섬유사이의 구멍이 작아질수록 압력강하가 커지고, 숨쉬기 힘들어진다. 이러한 단점을 보완하기위해 마스크에 정전기력을 이용하여 입자를 포집하기 시작했다. 정전기는 마스크의 여과기전 중 20-30% 정도를 차지하나, 더 미세한 입자를 거르기 우세하다. 하지만 정전기는 장기간 수분에 노출되거나 하전입자와의 접촉 등 다양한 요인들로 감소한다. 이에 본 연구의 목적은 시간경과, 온도, 습도 그리고 입자 노출에 따른 마스크의 정전기와 여과효율을 파악하고, 둘간의 상관성을 평가하고자 한다.

연구 방법 시험 마스크 선정은 4개 제조사의 1급 방진마스크(산업용)와 KF-94(보건용)마스크를 선정했다. 먼저, 마스크 여과효율에 관여하는 정전기의 영향을 보기 위해, 이소프로판올을 이용하여 정전기를 제거했다. 정전기를 제거하기 전과 후 마스크의 여과효율을 비교했다. 시간 경과 영향을 보기 위해 하룻동안 마스크 착용 온·습도 조건에 8시간을 노출시킨 후 16시간 동안은 상온에 보관했다. 이를 1, 2, 4, 8일 동안 반

복했다. 그 다음 습도와 온도의 영향을 보기 위해 온도를 25℃로 고정시키고, 습도 30, 50, 98%에 노출시켰고, 습도를 50%로 고정시키고, 온도 −30, 50, 70℃에 노출 시켰다. 마지막으로, 실제 착용한 마스크를 연구하기 위해 10명의 참가자를 모집하여 1, 2, 4일을 착용 시킨 후 수거했다. 이때 착용 시 성별, 착용시간, 행동 등을 기록했다. 마스크의 정전기는 표면전위 측정기를 이용해 마스크의 겉 표면과 마스크를 자른 후 내부 필터 층별로 측정했고, 여과효율은 필터테스터를 이용하여 NaCl과 파라핀 오일에 대한 여과효율을 보았다.

연구 결과 마스크의 정전기를 제거한 결과, 산업용마스크의 여과효율은 21.72%, 보건용마스크는 19.53%만큼 감소했다. 시간경과에 따라 한 제품을 제외한 마스크에서 정전기의 감소가 보였으나, 여과효율의 감소는 한 보건용마스크에서 관찰됐다($p<0.001$). 이 마스크의 8일 경과 후 여과효율은 94% 이하로 감소했다. 습도에 따른 정전기와 여과효율은 모두 감소했다. 산업용과 보건용마스크 모두에서 유의한 차이가 보였다($p<0.05$). 온도에 따른 마스크의 정전기와 여과효율은 습도조건에서와 달리 유의한 차이가 나타나지 않았다($p>0.05$). 한 개의 보건용마스크에서만 여과효율의 감소가 있었다($p<0.05$). 실제 착용한 마스크는 착용 기간이 증가함에 따라 정전기와 여과효율 각 11.26와 6.51%정도 감소했다. 압력강하 또한 시간이 증가함에 따라 감소했다(10.29%). 상관성 분석 결과 습도조건에서 강한 양의 상관성을 보였고, 온도조건에서는 약한 상관성을 보였다. 고습환경에서 마스크의 여과효율 감소는 정전기 감소로 설명되었으나, 고온에서 마스크 여과효율 감소는 정전기 보다는 마스크 성질이 변형되어 다른 기전의 기여로 보였다.

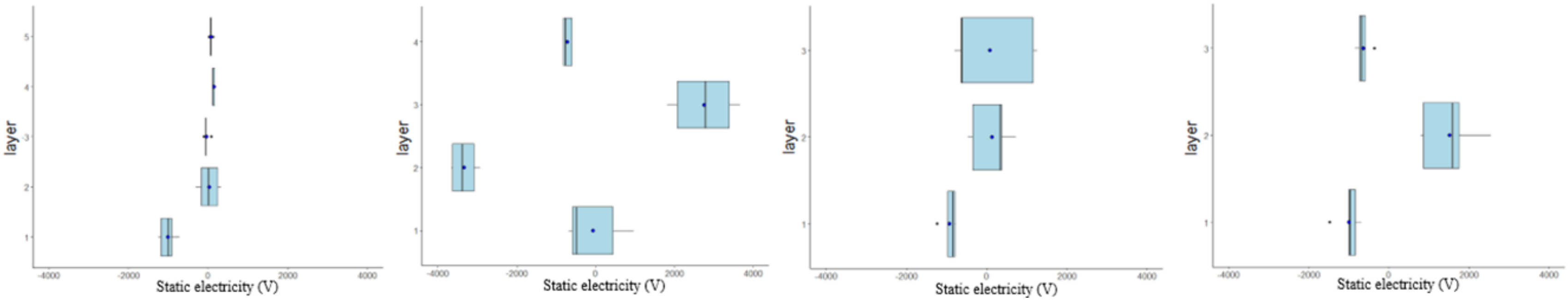
결론 마스크의 정전기와 여과효율의 감소는 습도가 높아짐에 따라 감소율이 가장 높았으며, 그 다음 시간경과 그리고 온도 순 이였다. 상관성 역시 습도조건에서 가장 강했으며, 온도조건에서 가장 약했다. 본 연구의 결과는 마스크 시험 시 고려되어야 할 필요가 있다. 또한, 마스크 필터 내부의 정전기를 보유하기 위한 기술 발전이 앞으로도 계속 필요하다.

주요어: 마스크, 호흡보호구, 여과효율, 여과기전, 정전기, 필터 테스트
학번: 2019-29004

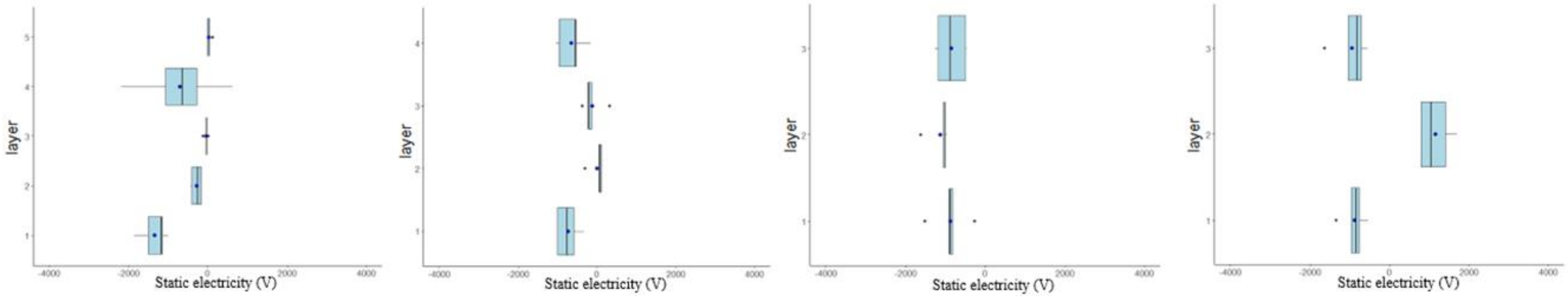
Appendix

Appendix 1. Initial static electricity of respirators

(a) 1st class

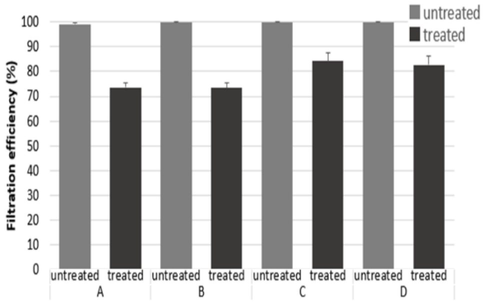


(b) KF-94

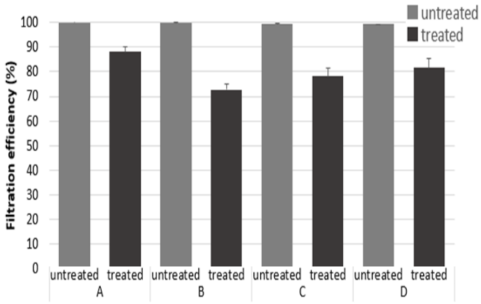


A **B** **C** **D**

Appendix 2. Filtration efficiency before and after IPA treatment in (a) 1st class and (b) KF-94. Error bars show standard deviation



(a) 1st class



(b) KF-94

Appendix 3. Pressure drop before and after IPA treatment

	Pressure drop (mmH_2O)					
	1st class			KF-94		
Manufacturer	Untreated (Mean ± SD)	Treated (Mean ± SD)	P value	Untreated (Mean ± SD)	Treated (Mean ± SD)	P value
A	13.13±2.12	13.55±1.95		19.22±1.89	15.64±1.24	
B	12.55±1.32	13.20±2.60		10.42±0.71	13.01±1.71	
C	11.47±0.63	9.28±0.32	>0.05	9.76±1.47	9.13±0.26	>0.05
D	12.61±0.09	13.05±0.27		11.92±1.13	12.12±0.44	
Total	12.44±1.04	12.27±1.28		12.83±1.30	12.48±0.91	

Appendix 4. Pressure drop over time.

			Pressure drop (mmH2O)									
Day			1		2		4		8		P-value*	
Manufacturer	Class	N	NaCl (Mean ± SD)	Paraffin Oil (Mean ± SD)	NaCl (Mean ± SD)	Paraffin Oil (Mean ± SD)	NaCl (Mean ± SD)	Paraffin Oil (Mean ± SD)	NaCl (Mean ± SD)	Paraffin Oil (Mean ± SD)	NaCl	Paraffin Oil
A	1st Class	5	13.52± 0.62	10.79± 0.96	15.52± 0.12	14.21± 0.41	12.93± 0.97	13.01± 0.40	12.13± 0.32	12.47± 0.35	**0.001**	**0.001**
	KF-94	5	15.96± 0.74	14.13± 0.56	16.62± 0.74	15.88± 0.73	16.34± 0.55	15.88± 0.91	14.92± 0.89	15.49± 0.31	0.078	0.087
B	1st Class	5	10.05± 0.17	9.87± 0.49	11.03± 0.72	10.68± 0.21	11.29± 0.19	11.06± 0.32	12.08± 0.13	12.13± 0.57	**0.006**	**0.003**
	KF-94	5	13.53± 0.31	12.82± 1.17	9.46± 0.44	8.13± 0.36	8.32± 0.75	8.33± 0.43	8.19± 0.01	8.36± 0.19	**<0.001**	**0.001**
C	1st Class	5	9.09± 0.04	9.14± 0.01	9.59± 0.12	9.65± 0.68	9.47± 0.42	9.99± 0.19	9.37± 1.01	9.42± 0.22	0.825	0.247
	KF-94	5	10.23± 1.49	9.33± 0.76	8.40± 1.12	8.36± 0.05	9.40± 0.33	8.87± 0.64	8.81± 0.75	8.90± 0.25	0.247	0.237
D	1st Class	5	11.12± 1.28	10.57± 1.07	12.10± 0.85	11.47± 0.39	11.51± 0.22	10.89± 0.39	11.27± 1.01	11.22± 0.12	0.591	0.291
	KF-94	5	11.98± 0.28	11.83± 0.70	12.45± 0.26	11.50± 0.96	11.08± 0.13	10.97± 0.75	11.86± 0.35	11.91± 0.27	**0.002**	0.448

* $P<0.05$ and p values are based on ANOVA analysis (among 30, 50, 98 %)

Appendix 5. Static electricity of respirators in each layer according to RH.

Manufacturer	Class	Layer	RH (%) 30 Mean±SD (V)	RH (%) 50 Mean±SD (V)	RH (%) 98 Mean±SD (V)	Class	Layer	RH (%) 30 Mean±SD (V)	RH (%) 50 Mean±SD (V)	RH (%) 98 Mean±SD (V)
A	Class1 (N=5)	1	2025.63±119.61	1741±284.4	1455.5±317.57	KF-94 (N=5)	1	2449.25±1056.22	1804.5±692.52	1677.19±618.12
		2	377±128.67	304±175.16	193.5±33.94		2	466.88±297.02	418±300.98	288.5±72.41
		3	136.75±83.74	116±17.62	77.25±48.51		3	90.31±52.67	74±36.79	127.75±188.73
		4	90.31±62.43	98.75±17.47	45.5±20.13		4	1182.5±437.42	386.41±277.29	208±92.74
		5	48.33±29.36	55±20.62	29.06±19.93		5	73.25±48.22	44±27.28	35.25±30.25
		Total	2678.02±423.81	2314.75±515.27	1800.81±440.08		Total	4262.19±1891.54	2726.91±1334.85	2336.69±1002.26
B	Class1 (N=5)	1	702±77.7	719.25±310.16	659.13±317.09	KF-94 (N=5)	1	1220.94±566.55	908.25±417.73	670.75±271.92
		2	3427.25±224.68	2891.04±831.56	2682±507.52		2	164.06±55.55	77.25±17.46	38.25±17.91
		3	1933.75±605.6	1884.79±146.64	1324.75±415.04		3	530.63±387.44	94.75±59.08	51.25±25.18
		4	1643.75±358.08	1334.75±225.18	237.79±528.81		4	2308.5±510.44	1670.25±402.23	1300.25±443.55
		Total	7706.75±1266.07	6829.83±1513.54	4903.67±1768.46		Total	4224.13±1519.98	2750.5±896.52	2060.5±758.56
C	Class1 (N=5)	1	2382.75±531.88	1634±561.04	912.75±258.16	KF-94 (N=5))	1	1538.13±584.21	915.75±137.82	819.75±366.33
		2	1015±186.38	928.5±207.74	395.53±236.07		2	1230.75±296.06	984.73±324.31	952.75±330.45
		3	1438.75±404.23	923.25±199.64	693±232.11		3	1237±271.06	1162.29±235.41	964.75±215.48
		Total	4836.5±1122.49	3485.75±968.41	2001.28±726.34		Total	4005.88±1151.32	3062.77±697.54	2737.25±912.26
D	Class1 (N=5)	1	1163.54±385.7	1040.94±372.16	600.75±231.65	KF-94 (N=5)	1	1192.38±234.89	1077±317.14	644.75±266.3
		2	1768±680.49	1334.38±254.77	756.25±245.98		2	1927.81±1102.58	1069.69±408.55	468.75±258.45

3	1359.69±693.41	636±70.28	309.38±81.29	3	887.38±270.35	865.5±223.78	497.75±257.91
Total	4291.22±1759.61	3011.31±697.21	1666.38±558.93	Total	4007.56±1607.82	3012.19±949.48	1611.25±782.66

Appendix 6. Static electricity of respirators in each layer depending on temperature.

Manufacturer	Class	Layer	Temperature (℃)			Class	Layer	Temperature (℃)		
			-30	25	70			-30	25	70
			Mean±SD (V)	Mean±SD (V)	Mean±SD (V)			Mean±SD (V)	Mean±SD (V)	Mean±SD (V)
A	Class1 (N=5)	1	2160.42±451.74	1741±284.4	1455.5±317.57	KF-94 (N=5)	1	2339.58±322.12	1804.5±692.52	2955±1082.71
		2	727.5±295.23	304±175.16	193.5±33.94		2	499.58±396.53	418±300.98	432.19±123.1
		3	205±156.12	116±17.62	77.25±48.51		3	54.58±14.43	74±36.79	116.43±85.95
		4	110.42±21.52	98.75±17.47	45.5±20.13		4	2215.83±1991.77	386.41±277.29	208.75±117.91
		5	133.75±23.75	55±20.62	29.06±19.93		5	247.92±238.31	44±27.28	29.38±25.68
		Total	3337.08±948.36	2314.75±515.26	1800.81±440.08		Total	5357.5±2963.17	2726.91±1334.85	3741.74±1435.35
B	Class1 (N=5)	1	1487.08±433.13	719.25±310.16	1385.25±212.86	KF-94 (N=5)	1	1681.67±183.17	908.25±417.73	2239.82±899.36
		2	1800.83±293.18	2891.04±831.56	3283.75±614.88		2	254.58±58.98	77.25±17.46	166.88±54.93
		3	1327.5±605.27	1884.79±146.64	998.25±386.79		3	1116.25±704.62	94.75±59.08	800.71±599.5
		4	1520±450.38	1334.75±225.18	1917±163.7		4	3250±343.92	1670.25±402.23	3690.18±1013.6
		Total	6135.42±1781.96	6829.83±1513.54	7584.25±1378.23		Total	6302.5±1290.68	2750.5±896.52	6897.59±2567.39
C	Class1 (N=5)	1	2544.58±232.97	1634±561.04	1584.25±1095.34	KF-94 (N=5))	1	1616.67±298.32	915.75±137.82	2468.93±663.09
		2	647.5±152.99	928.5±207.74	595.5±550.59		2	1489.58±248.75	984.73±324.31	1518.39±464.37

		3	832.5±165.66	923.25±199.64	1308.25±507.34		3	1625.42±118.82	1162.29±235.41	2233.39±690.59
		Total	4024.58±551.61	3485.75±968.41	3488±2153.27		Total	4731.67±665.9	3062.77±697.54	6220.71±1818.05
D	Class1 (N=5)	1	2127.08±91.07	1040.94±372.16	1598±343.73	KF-94 (N=5)	1	1893.75±527.04	1077±317.14	1343.33±358.26
		2	1237.5±351.74	1334.38±254.77	817.75±423.16		2	629.58±140.45	1069.69±408.55	863.13±562.62
		3	1835±252.25	636±70.28	1918.25±322.69		3	1351.25±152.13	865.5±223.78	1481.35±617.54
		Total	5199.58±695.07	3011.31±697.21	4334±1089.58		Total	3874.58±819.62	3012.19±949.48	3687.81±1538.41

Appendix 7. Pressure drop of respirators according to RH.

			Pressure drop (mmH_2O)							
RH (%)			30		50		98		P-value*	
Manufacturer	Class	N	NaCl (Mean ± SD)	Paraffin Oil (Mean ± SD)	NaCl (Mean ± SD)	Paraffin Oil (Mean ± SD)	NaCl (Mean ± SD)	Paraffin Oil (Mean ± SD)	NaCl	Paraffin Oil
A	1st Class	5	13.26±0.51	13.42±2.69	12.14±1.65	13.78±1.20	10.58±0.86	11.30±0.98	**0.038**	0.323
	KF-94	5	14.40±0.02	14.22±1.06	17.24±0.51	15.83±0.42	16.18±1.18	15.23±0.79	**0.011**	0.12
B	1st Class	5	11.25±1.09	10.63±0.52	12.78±0.24	12.61±0.36	11.52±0.58	12.48±0.46	0.086	**0.001**
	KF-94	5	9.41±0.57	8.64±0.43	9.07±0.24	8.80±0.25	8.87±0.18	8.62±0.36	0.271	0.794
C	1st Class	5	10.34±0.67	9.86±0.48	10.02±0.57	9.49±0.26	9.45±0.76	10.51±1.04	0.238	0.19
	KF-94	5	9.09±0.82	9.39±0.73	9.22±0.40	9.57±0.64	9.18±1.05	9.45±0.60	0.976	0.923
D	1st Class	5	12.66±2.38	13.14±0.71	12.40±1.65	14.11±1.29	10.73±0.11	13.3±1.59	0.502	0.684
	KF-94	5	10.38±0.88	9.12±0.64	11.27±0.44	10.84±0.16	10.82±0.11	10.74±0.16	0.176	**0.004**

* $P<0.05$ and p values are based on ANOVA analysis (among 30, 50, 98 %)

Appendix 8. Pressure drop of respirators according to temperature.

			Pressure drop (mmH_2O)							
Temperature (℃)			-30		25		70		P-value*	
Manufacturer	Class	N	NaCl (Mean ± SD)	Paraffin Oil (Mean ± SD)	NaCl (Mean ± SD)	Paraffin Oil (Mean ± SD)	NaCl (Mean ± SD)	Paraffin Oil (Mean ± SD)	NaCl	Paraffin Oil
A	1st Class	5	11.80±1.24	11.81±1.24	12.14±1.65	13.78±1.20	11.02±1.06	12.96±1.05	0.698	0.264
	KF-94	5	14.24±1.34	15.53±2.89	17.24±0.51	15.83±0.42	16.11±0.36	16.32±0.30	**0.016**	0.801
B	1st Class	5	10.15±1.12	9.32±0.37	12.78±0.24	12.61±0.36	12.45±1.01	12.39±0.42	**0.037**	**0.001**
	KF-94	5	8.71±0.62	8.56±0.42	9.07±0.24	8.80±0.25	9.86±0.18	9.14±0.09	**0.028**	0.119
C	1st Class	5	10.82±0.18	10.53±0.52	10.02±0.57	9.49±0.26	9.24±0.34	10.10±0.48	**0.025**	0.068
	KF-94	5	10.40±0.40	9.55±0.94	9.22±0.40	9.57±0.64	9.09±0.24	8.79±0.61	**0.019**	0.359
D	1st Class	5	11.40±0.35	11.43±0.56	12.4±1.65	14.11±1.29	10.93±1.27	11.24±1.30	0.445	0.059
	KF-94	5	12.54±0.79	12.16±0.32	11.27±0.44	10.84±0.16	10.65±0.15	10.52±0.29	**0.011**	**0.002**

* $P<0.05$ and p values are based on ANOVA analysis (among 30, 50, 98 %)

Appendix 9. The correlation analysis r values for each product between static electricity in each layer total of respirator and filtration efficiency. (a) is 1st class for occupational using. (b) is KF-94 for public using.

(a)

	A	B	C	D
Aging	0.664185	0.753337	0.518715	P < 0.05
Humidity	0.963376	0.497894	0.950336	0.770454
Temperature	P < 0.05	P < 0.05	0.592149	P < 0.05

(b)

	A	B	C	D
Aging	0.714123	0.662688	P < 0.05	P < 0.05
Humidity	0.604914	0.529282	0.801285	0.794363
Temperature	0.836391	P < 0.05	0.592302	P < 0.05

Appendix 10. The correlation analysis r values for each product between static electricity on the outer surface of respirator and filtration efficiency. (a) is 1st class for occupational using. (b) is KF-94 for public using.

(a)

	A	B	C	D
Aging	0.4858722	0.6608459	0.7086434	0.6263064
Humidity	0.7518897	0.6128627	0.7981608	0.7170065
Temperature	P < 0.05	0.6592602	0.5407701	0.7817216

(b)

	A	B	C	D
Aging	0.563377	0.6496287	0.5949921	0.6119182
Humidity	0.7559289	0.6186776	0.7456295	0.8804176
Temperature	0.5293859	P < 0.05	P < 0.05	0.7766852