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Filtering efficiency measurement of respirators by laser-based particle counting method

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ABSTRACT

Respirators are one of the most useful personal protective equipment which can effectively limit the spreading of coronavirus (COVID-19). There are a worldwide shortage of respirators, melt-blown non-woven fabrics, and respirator testing possibilities. An easy and fast filtering efficiency measurement method was developed for testing the filtering materials of respirators. It works with a laser-based particle counting method, and it can determine two types of filtering efficiencies: Particle Filtering Efficiency (PFE) at given particle sizes and Concentration Filtering Efficiency (CFE) in the case of different aerosols. The measurement method was validated with different aerosol concentrations and with etalon respirators. Considerable advantages of our measurement method are simplicity, availability, and the relatively low price compared to the flame-photometer based methods. The ability of the measurement method was tested on ten different types of Chinese KN95 respirators. The quality of these respirators differs much, only two from ten reached 95% filtering efficiency.

1. Introduction

The ambient air is full of different biological and non-biological aerosol particles, like viruses, bacteria, fungal spores, pollens, and simple fragments. The size of these aerosol particles varies between 0.1 and 10 µm, so without personal protection, they can easily penetrate the human respiratory system and may cause health issues, especially in the wear of personal protective equipment in closed and crowded spaces between human individuals [5–8]. The latest worldwide public health problem is caused by the 2019 novel coronavirus (COVID-19), which has a particle size between 0.06 and 0.14 µm [3]. COVID-19 infection is mostly transmitted by direct mucosal contact to droplet-borne viruses originating from the mouth or nose of an infected person [4]. Therefore, some of the latest researches revealed that surgical masks and respirators could prevent or at least slow down the transmission of COVID-19 between human individuals [5–8]. Most of the governments suggest the wear of personal protective equipment in closed and crowded spaces like public buildings and transportations. In the case of a lack of personal protective equipment, it is mandatory to wear face coverings or so-called community masks. Such devices have low to no filtration efficiency, and they are perceived more as a hygienic measure that minimizes the projection of user’s respiratory droplets saliva, sputum, or respiratory secretions when talking, coughing, or sneezing [9,10].

The respirators are classified according to their filtering efficiency. The European Respirator Standard (EN 149:2001) distinguishes three classes: FFP1 (Filtering FacePiece), FFP2, and FFP3 with corresponding minimum filtration efficiencies of 80%, 94%, and 99%, with a test agent, which has 0.4 and 0.6 µm median mass aerodynamic diameter [11]. The US versions are the N95 and N100 respirators (having 95% and 100% filtering efficiency) [12], according to the NIOSH-42C FR84 standard. The Chinese version is the KN95 (having 95% filtering efficiency), according to the GB2626-20 06 standard. Although the standards slightly differ in the determination methods of the filtering efficiency, the FFP2, N95, and KN95 respirators can suppose to be equivalent [13]. Generally, respirators are built up from two outer textile layers, which do not have any filtering role, and 1–2 inner filter layers, which can block liquid and solid particles as well (valid for EU tested respirators) [14]. (In the US, there is a distinction between the respirators that can be used to protect against both groups of contaminants.) The most essential and complicated layer is always the particle filter layer, which was usually made from melt-blown polypropylene microfibers [15]. The application of microfibers has limitations in filtering efficiency. Although the filtering efficiency could be improved with the increase of the thickness of the filter material, it decreases the breathability of the respirator [16]. Polypropylene electret melt-blown nonwovens are also
applied, which could have increased filtration efficiency by electrostatic forces without sacrificing the air resistance [17]. In the case of FFP3 respirators, usually, exhalation valves needed to be used to avoid the lack of O₂ and the accumulation of CO₂. The application exhalation valves have high health risks in a pandemic, since it lets out the exhaled air to the environment, so the protection of the mask is only one way. Therefore, some of the EU states already banned the marketing of respirators with exhalation valves. Recent researches showed that the electrospon nanofiber webs (mostly from polyacrylonitrile) are alternate candidates for filter materials due to their small pore size, small diameter, and large specific surface area [18,19].

The fast-spreading of COVID-19 caused a worldwide shortage of respirators, melt-blown non-woven fabrics, which are the raw material of the mask filters, and the respirator testing possibilities. The lack of respirators initiated to search for emergency solutions. The most obvious is the possible reuse of respirators with some decontamination methods. Bokoski et al. [20] suggested using highly energetic, shortwave, ultraviolet germicidal irradiation at 254 nm to decontaminate N95 respirators from viral agents. Grossman et al. [21] extended the wear life of N95 respirators using vaporized hydrogen peroxide (VHP) disinfection. Juand and Tsai [22] suggested heating to 70 °C or boiling the N95 respirators, which processes do not change the filtering efficiency, and they are against the use of soap or alcohol for disinfection. However, most of the studies agree that the reuse of respirators should only be practiced as a crisis capacity strategy [20–23]. In addition, Suen et al. [24] reported a significant fit factor and filtering efficiency drop of N95 respirators after nursing procedures. Ho et al. [25] found that the simple homemade cotton masks could be a temporary solution since they can block the respiratory droplets effectively. Different custom-made mask frames with changeable filters are also appeared on the market [26].

The lack of respirators also caused the partially controlled inflow of different chines respirators into the EU; most of them were marked as KN95. Some EU member states reported quality problems directly after the arrival of them. Therefore, re-qualifying these respirators are essential before using them. In 2020, only eleven laboratories had the accreditation for EN 149:2001 standard in the EU. They are overloaded, so there is a strong need for capacity building. The EN 149:2001 standard measures the filtering efficiency with a photoelectric flame photometer. The flame photometer can determine the concentration of certain metal ions, mainly from groups 1 and 2, which have low excitation energies, like sodium, potassium, lithium, and calcium. It is a controlled flame test, the investigated material is vapourised, and the intensity of the flame color depends on the energy that had been absorbed [27]. This method is well used for decades. However, it is relatively expensive, can analyze only metals, and cannot give any information about the analyzed particle sizes, which would be important in the case of infection blocking of respirators.

Particle counting methods are also already used in laboratory practice. Rengasamy et al. [28] compared the penetrations of N95 respirators by photometric and by ultrafine condensation particle counting (UCPC) methods. They found that the penetration values obtained using the UCPC are more accurate in the case of the photometric method, which lacks sensitivity for small particles (<100 nm). Kim et al. [29] also used the UCPC method successfully to detect nanoparticles (3–20 nm) penetration through commercial filter media. However, in the case of UCPC methods, usually low volume flow rates are used. The standard operating flow rate is 0.30 to 0.5 l/min, which is far from the volume flow rate during the use of the respirators [30]. Balazy et al. [1] built a combined system, from a differential mobility diameter, from a condensation particle counter, and from a laser particle spectrometer. The combined machine lowered the measurable particle range between 10 and 1000 nm, but this solution does not suggest an easy and commercial use. Our aim was to develop a fast and easy filtering efficiency measurement method based on particle counting, which could help the respirator’s classification during COVID-19 pandemic.

2. Methods

2.1. The measurement method and the system

Our method determines the filtering efficiency of the filtering material of the respirators, which is one of the most important parameters of a mask. It has to be noted that further important parameters of the masks have not been covered in this study, like inward leakage as a measure of fit to the wearer’s face [12], breathing resistance, and efficient exchange of CO₂ under the facepiece. Our measurement method is based on particle counting. It is destructive from the point of ready respirators. A sample needs to be cut out from the filtering material of the investigated mask. The main parts of the measurement system are a particle counter (LASAIR III 310C) and a self-designed 3D printed sample holder that fixes the investigated filter material during the measurements. Fig. 1 shows the measurement system.

The surface size of the sample holder is 50 × 70 mm, and it has four main parts: bottom holder, upper holder, O ring, and fixing screws. The inner and outer diameter of the O ring is 20 and 26 mm, respectively. A 35 × 35 mm sample is positioned over the O ring. It keeps the sample during the measurement and blocks the leakage between the bottom and upper parts of the sample holder. So the ambient air is sucked only through the sample. The O ring sits in a riffle, which sinks the O ring 1.5 mm into the bottom holder to ensure the optimal fixing of it. The fixing screws push the upper part to the bottom together with the sample and the O ring. The assembled sample holder is connected to the particle counter with the suction tube and suction pipe (Fig. 1).

The Lasair III 310C is a portable aerosol particle counter which is usually used to qualify clean-rooms in microelectronics or medicine production [31]. It works with a laser-based counting method. The accessing particle in the device passes through laser light. A photodetector detects the redirected light and the loss of the light, which determines the size of the obstructing particle. Finally, the particle counter distinguishes the counted particles according to the estimated sizes into channels. The used particle counter has six channels with the following particle size ranges: 0.3–0.5 µm, 0.5–1 µm, 1–5 µm, 5–10 µm, 10–25 µm, and 25 µm >, respectively. In a given particle size range, there is no information about the exact particle distribution.

The volume flow rate of the device is 30 l/min, which is approximately the average breathing flow of humans in a resting position. The measurement contained two steps. First, the Particle Number Concentration (PNC) (pcs./m³) of the ambient air is measured for 1 min. Right after, the sample holder is installed on the particle counter, and the PNC behind the filter material is measured again for 1 min. The filtering efficiencies are determined respectively from the PNC differences.

A considerable advantage of our measurement method is simplicity, since it can be installed in a few days, availability of the particle counter device on the present market, and the low price (~15,000–18,000 USD) compared to the filtering efficiency measurement system according to the EN 149:2001 standard (~60,000–100,000 USD).

2.2. Determination of the filtering efficiency

Contrary to the flame photometer based measurement methods, our particle counter measurement method can determine not only one but two different filtering efficiencies. The Particle Filtering Efficiency (PFE, %) can be measured on all channels of the particle counter. It is defined as:
defined as:

\[
\text{CFE} = \left( \frac{\text{PC}_A - \text{PC}_C}{\text{PC}_A} \right) \times 100 \% \tag{2}
\]

where \( \text{PC}_A \) is the particle concentration of the ambient air \([\text{mg/m}^3]\), and \( \text{PC}_C \) is the particle concentration behind the filter material \([\text{mg/m}^3]\). The particle counter can measure particle number concentrations (PNC) directly; the particle concentrations (PC) can be calculated from the PNCs and the particle sizes. (During the calculations, it was assumed that the specific density of the particles in the ambient air is near homogeneous).

### 2.3. Investigated respirators

The investigated respirators were distinguished into two groups: a reference group that contains three different FFP2-3 respirators with certificates according to the EN 149:2001 standard and an unknown group, which includes ten different KN95 respirators without a european certificate. Table 1 shows the known information about the investigated respirators. Ten samples were tested from each mask type, and the measurements were half-blind.

### 3. Results and discussion

#### 3.1. Particle number concentration and size distribution of the ambient air

The measurements are carried out by the ambient air; therefore, it is important to know how the PNC and the particle size distribution changes from day to day. These parameters are influenced by a lot of factors, e.g. the weather or the traffic level around the measurement location. The investigations were carried out for two months in different environmental conditions. PNCs and particle size distributions were measured in rainy and dry weather, in cold and hot weather, and at low and high traffic levels. Altogether more than 300 measurement results were used. It was found that the PNC changed from between \(1 \times 10^7\) (clear air) and \(5 \times 10^7\) (polluted air) at our measurement location (Budapest). The particle size distribution in the function of PNC can be seen in Fig. 2 that uses a logarithmic scale due to the high differences.

The particle size distribution was almost constant in the range of the PNC between \(2 \times 10^7\) and \(5 \times 10^7\). The majority of the particles (~98%) were smaller than 1 \(\mu\)m, the ratio of the particles between 1 and 5 \(\mu\)m was around ~1.5%, and only 0.5% was bigger than 5 \(\mu\)m. The EN 149:2001 standard defines CFE values in the case of aerosols with 0.4 and 0.6 \(\mu\)m MMAD (Median Mass Arodinamic Diameter). Our analysis of the MMAD parameter showed that in the \(2 \times 10^7\)–\(5 \times 10^7\) PNC range, the MMAD was between 0.34 and 0.76 \(\mu\)m, if only the particles between 0.3 and 5 \(\mu\)m were counted. It is close to the requirements of EN 149:2001 standard. Therefore only the PNC between \(2 \times 10^7\) and \(5 \times 10^7\) were used during the measurements, and the particle concentrations (PC) were counted only from the 0.3–5 \(\mu\)m range during the CFE calculations. It has to be noted that we usually measured with a finer aerosol but with a lower flow rate (30 l/min) than the EN 149:2001 standard (95 l/min). These differences did not have a considerable effect on the measured results compared to the results of the standard EN149:2001 method (See in Section 3.2).

![Fig. 1. The measurement system: the build-up of the sample holder and the particle counter machine.](image)

Table 1

| Number | Group      | Type   | CFE       | Standard      | Manufacturer |
|--------|------------|--------|-----------|---------------|--------------|
| R1     | Reference  | FFP2   | ≥94%      | EN149:2001    | 3M           |
| R2     | Reference  | FFP2   | ≥94%      | EN149:2001    | Uvex         |
| R3     | Reference  | FFP3   | ≥99%      | EN149:2001    | Shelco Filters |
| U1-10  | Unknown    | KN95   | ≥95%      | GB2626-20 06  | China*       |

* In the case of the chinse respirators, the manufacturers were usually unknown or unsure.

![Fig. 2. Particle number distribution in the function of PNC, measured for two months at different environmental conditions in Budapest.](image)
3.2. Validation of the measurement method

The validation steps of the measurement were done by the reference respirators (R1-R3). The repeatability of the measurements was investigated in the case of $4 \times 10^7$ PNC. It was found that the repeatability slightly depends on the particle sizes. Two ranges of particle sizes could be distinguished (0.3–5 µm and 5–25 µm), wherein the repeatability errors differ. However, they are very low in both ranges: lower than 0.05% in the range of 0.3–5 µm size particles and lower than 0.5% in the range of 5–25 µm size particles.

The PNC of the ambient air is hardly controllable; it is very important that the measurement cannot be too sensitive to this parameter. So it was also investigated whether the PNC of the ambient air affects the filtering efficiency of the filter materials. All the above-mentioned PNC values ($1 \times 10^7$–$5 \times 10^7$) were investigated. Table 2, shows the filtering efficiencies of the R3 reference filtering material (FPP3 respirator) at different PNCs. The filtering efficiency did not show sensitivity to the PNC between $1 \times 10^7$ and $5 \times 10^7$. Therefore, the measurements were executed at the given particle-number concentration on the given day (practically between $2 \times 10^7$ and $5 \times 10^7$).

Finally, the measurement method was tested with certified filtering materials. Table 3 shows the filtering efficiencies of the R1-R3 filtering materials. The measured CFE values were always slightly over the guaranteed CFE values by the manufacturer. It could be the over-insurance of the filtering materials due to the inward leakage of the respirator, or it could be due to the applied lower flow rate.

According to the validation results, it can be stated that our measurement method is a stable and capable method to investigate unknown respirators.

3.3. Analyses of the KN95 masks in Europe

Fig. 3 shows the CFE values of filtering material in the U1-10 “unknown” Chinese KN95 respirators. The respirators were distinguished into three categories. Two KN95 respirators reached the 95% CFE value (passed category, green in Fig. 3), and these two exceeded it considerably with ~98% (like in the case of the reference FFP2 respirators in Table 3). Four KN95 respirators exceeded the 90% CFE (almost passed category, yellow in Fig. 3). Four KN95 respiratory were under 90% CFE; one showed only 64% CFE (failed category, red in Fig. 3). In the failed category, the deviation of the filtering efficiencies was usually large, which also indicates the quality problems.

The particle filtering efficiencies (PFE) of the U1-10 “unknown” filtering materials were also investigated (Table 4) to find the relation between CFE and PFE performance of the respirators. In the case of the passed respirators (green in Fig. 3), the PFE values were over 95% on each particle size range. In the case of the almost passed respirators (yellow in Fig. 3), the PFE of the 0.3–0.5 µm range never reached 95%. It was between 75 and 90%. Since the majority of the particles are in this size range, it caused the unlikely decrease of the CFE values below 95%.

The PFE values of the larger particle size ranges (>0.5 µm) were over 95%. In the case of the failed masks (red in Fig. 3), the filter materials of

| Table 2 |
| --- |
| **Filtering efficiencies of R3 reference filtering material at different PNCs.** |
| PNC (pcs./m³)/Sample | 1 × $10^7$ | 2 × $10^7$ | 3 × $10^7$ | 4 × $10^7$ | 5 × $10^7$ |
| PFE at 0.3-0.5 µm (µm) | 0.05 0.07 0.05 0.07 0.07 |
| PFE at 0.5-1 µm (µm) | 0.04 0.05 0.05 0.03 0.03 |
| PFE at 1-5 µm (µm) | 0.07 0.08 0.08 0.04 0.05 |
| PFE at 5-10 µm (µm) | 0.17 0.25 0.15 0.25 0.11 |
| PFE at 10-25 µm (µm) | 0.67 0.72 0.44 0.84 0.38 |
| PFE at 25 µm (µm) | 100 ± 0 100 ± 0 100 ± 0 100 ± 0 100 ± 0 |
| CFE at 0.3–5 µm (µm) | 99.67 ± 0.67 99.68 ± 0.68 99.68 ± 0.69 99.65 ± 0.65 |
| PFE at 0.3–5 µm (µm) | 0.06 0.07 0.08 0.05 0.05 |

| Table 3 |
| --- |
| **Filtering efficiencies (PFE and CFE) of the R1-R3 reference filtering materials.** |
| PNC (pcs./m³)/Sample | R1 (FFP2) | R2 (FFP2) | R3 (FFP3) |
| --- |
| PFE at 0.3–0.5 µm (µm) | 92.86 ± 1.63 93.23 ± 0.76 99.45 ± 0.07 |
| PFE at 0.5–1 µm (µm) | 98.11 ± 0.64 98.55 ± 0.22 99.77 ± 0.03 |
| PFE at 1–5 µm (µm) | 99.77 ± 0.11 99.87 ± 0.02 99.90 ± 0.04 |
| PFE at 5–10 µm (µm) | 99.72 ± 0.15 99.51 ± 0.2 99.78 ± 0.25 |
| PFE at 10–25 µm (µm) | 99.55 ± 0.32 99.58 ± 0.42 99.78 ± 0.84 |
| CFE at 0.3–5 µm (µm) | 97.65 ± 0.58 97.79 ± 0.28 99.63 ± 0.05 |

| Table 4 |
| --- |
| **Particle Filtering Efficiencies (PFE) of the U1-10 Chinese KN95 respirators.** |
| PNC (pcs./m³)/Sample | U1 (CFE) | U2 (CFE) | U3 (CFE) | U4 (CFE) | U5 (CFE) |
| --- |
| 1 × $10^7$ | 98.42 1.29 1.53 7.92 1.97 |
| 2 × $10^7$ | 99.12 ± 0.23 3.6 3.02 1.93 0.36 |
| 3 × $10^7$ | 99.73 ± 0.04 0.28 0.06 0.83 0.27 |
| 4 × $10^7$ | 99.93 ± 0.32 0.66 0.38 0.35 0.18 |
| 5 × $10^7$ | 99.75 ± 0.24 0.59 0.27 0.38 0.3 |
| U6 (CFE) | 64.71 1.29 1.53 7.92 1.97 |
| U7 (CFE) | 98.38 ± 0.83 0.35 0.83 0.54 1.55 |
| U8 (CFE) | 99.78 ± 1.18 0.05 0.86 0.17 0.61 |
| U9 (CFE) | 99.73 ± 0.32 0.66 0.38 0.35 0.18 |
| U10 (CFE) | 99.75 ± 0.24 0.59 0.27 0.38 0.3 |
| U11 (CFE) | 99.78 ± 1.18 0.05 0.86 0.17 0.61 |
| U12 (CFE) | 99.79 ± 1.29 1.53 7.92 1.97 |

![Fig. 3. Concentration Filtering Efficiency (CFE) of the U1-10 Chinese KN95 respirators.](image-url)
the respirators were usually not efficient enough in the 0.3–1 μm range. In the 0.3–0.5 μm range, PFE values were only between 45 and 80%, and in the 0.5–1 μm range, it was between 80 and 95%. Between 1 and 25 μm particle size range, all respirators could perform sufficient PFE values (>95%), and over 25 μm, all the particles were filtered. Consequently, the PFE values can predict the CFE value well; they could be used during the development of the filter materials.

4. Conclusions

A fast and easy measurement method was developed to determine the filtering efficiency of respirators applied during COVID-19 pandemic. It is based on laser particle counting. The different validation tests proved that our measurement method could determine the concentration filtering efficiency (CFE) of the filter materials of the respirators similarly to the EN 149:2001 standard. Furthermore, our method can provide the particle filtering efficiency (PFE) on six particle size ranges, which is additional information compared to the flame photometry. The PFE values show the strengths and weaknesses of the respirators in given particle size ranges, so PFE could help to develop the respirators’ filtering efficiency further. Consideration further. Consideration of our measurement method are simplicity, availability, and the much lower price compared to the flame-photometer based methods. The analysis of the ten different types of chinese KN95 respirators showed that only two types could reach the theoretical 95% CFE value. Four types were over 90%, and the last four were under 90%. The failed respirators could not perform acceptable CFE in the 0.3–1 μm particle size range. These results suggest the more strict control of the KN95 respirators on the EU market.

The work will be continued by the extension of our method with breathing resistance and inward leakage measurements and by supporting nano-filter breathing medium researches with filtration measurements.

CRedit authorship contribution statement

Balazs Illes: Conceptualization, Methodology, Software, Writing - original draft, Writing - review & editing. Peter Gordon: Data curation, Validation, Visualization, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] A. Balazs, M. Toivola, A. Adhikari, S.K. Sivasubramani, T. Reponen, S. A. Grinshpun, Do N95 respirators provide 95% protection level against airborne viruses, and how adequate are surgical masks? Am. J. Infect. Control. 34 (2006) 51–57, https://doi.org/10.1016/j.ajic.2005.08.018.
[2] Y. Xiang, Q. Song, W. Gu, Decontamination of surgical face masks and N95 respirators by dry heat pasteurization for one hour at 70°C, Am. J. Infect. Control. 48 (2020) 880–882, https://doi.org/10.1016/j.ajic.2020.05.026.
[3] N. Zhu, B. Zhang, W. Wang, et al., A novel coronavirus from patients with pneumonia in China, N. Engl. J. Med. 382 (2020) 727–733, https://doi.org/10.1056/NEJMa2001017.
[4] R. Wölfel, V.M. Corman, W. Guggemos, et al., Virological assessment of hospitalized patients with COVID-19, Nature 581 (2020) 465–469, https://doi.org/10.1038/s41586-020-2156-x.
[5] M. Ippolito, F. Vitalé, G. Accurso, P. Iozzo, C. Gregoretti, A. Giarratano, A. Cortegiani, Medical masks and respirators for the protection of healthcare workers from SARS-CoV-2 and other viruses, Pulmonary Medicine 2020 (2020) 204–212, https://doi.org/10.1155/2020/4.009.
C. Kuang, M. Chen, P.H. McMurry, J. Wang, Modification of laminar flow ultrafine condensation particle counters for the enhanced detection of 1 nm condensation nuclei, Aerosol Sci. Technol. 46 (2012) 309–315, https://doi.org/10.1080/02786826.2011.626815.

B. Liu, W. Szymanski, K.-H. Ahn, On aerosol size distribution measurement by laser and white light optical particle counters, J. Environ. Sci. 28 (1985) 19–24, https://doi.org/10.17764/jiet.1.28.3.1b73425806586048.