Evaluation of filtering facepiece respirators using chemical decontamination methods

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Abstract. Disposable filtering facepiece respirators (FFRs) are often recommended for use by healthcare workers and the general public for infection control. During pandemic, shortage in supply of FFRs is reported due to excessive demand. Hence, suitable decontamination methods of used FFRs are required to be identified. Various chemical decontamination methods (isopropyl alcohol (IPA), vaporized hydrogen peroxide (VHP) and detergent) have been explored in the present study. The performance of the FFRs after exposed to three types of chemical decontamination methods was evaluated based on average aerosol penetration and average filter resistance values. Face mask type N95 and KN95 with four different models were used in the study. Based on the normalized data for filter aerosol penetration of the three decontamination methods, VHP is recommended to be used for decontamination methods for FFRs. Model 3 FFRs showed good performance where less deviation in the normalized filter aerosol penetration and normalized filter air flow resistance for the three decontamination methods was observed.

Keywords: Decontamination, filtering facepiece respirator, N95 respirator, KN95 respirator, filter

1. Introduction
In Malaysia, all employees are covered under the Occupational Safety and Health Act (OSHA 1994) [1] and the Factories and Machinery Act (FMA 1967) [2]. The Department of Occupational Safety and Health (DOSH) in the Ministry of Human Resources (MOHR) implements these acts to ensure the safety and health of the workers. Occupational Safety and Health Act 1994 is a legislative framework which enacted to secure the safety, health, and welfare of persons at workplace, to protect others from safety and health risk in activities pertaining to their workplace and to promote occupational safety and health culture in workplace. Part IV Section 15 in OSHA 1994 stated the responsibility of every employer to ensure safety, health and welfare of the employees at work which include provision of information, instruction, training and supervision. Occupational Safety and Health Act 1994 is not only acted as a legislation; it also acts as a reference for employers to aware and promote the company’s safety and health culture.
Occupational safety and health measures wearing suitable FFRs, it is important during epidemics or pandemics. Inadequate supply of FFRs become an issue especially in countries that are not the producer of FFRs. The pandemic of COVID-19 generates an unparalleled demand for N95 respirators in widespread usage [3]. The shortage of medical N95 respirators or other certified masks creates an urgent demand for suitable replacement [4]. The Centre for Disease Control and Prevention has issued guidance on maximizing stock supply by restricting use, reusing patients and providers, and making recommendations on alternative protective equipment [5]. Various decontamination techniques have been investigated to improve the security of FFRs reuse without compromising the capability and structural integrity of protective filtration. Testing of many other variants of N95 masks included in the strategic national inventory showed that they could resist sterilization process by using ultraviolet germicidal irradiation (UVGI), ethylene oxide, or vaporized hydrogen peroxide (VHP) while retaining the adequate protective role [6].

Studies on decontamination techniques of FFRs have gained attention from previous researchers. Viscoli et al. [7] assessed the filtration performance of N95 FFRs after isopropyl alcohol (IPA) decontamination at 2 different times of submersion (1 second and 1 minute). Performance of FFRs was also evaluated using soap and water at 2 different time intervals, using a poly-dispersed sodium chloride aerosol test method. Changes in physical appearance, odor and laboratory performance of six N95 FFR models after 3 cycles of decontamination using VHP have been studied by Bergman et al. [8]. Carlos et al. [9] reported that UVGI and VHP appear to be the most positive decontamination methods for N95 FFRs, based on their biocidal efficacy, filtration performance, fitting characteristics, and residual chemical toxicity, as well as other practical aspects such as the equipment required for their implementation and the number of decontamination cycles. In a recent study by Rafael et al. [10], they concluded that VHP and ultraviolet irradiation emerged to be the most favorable methods for N95 respirator decontamination.

Many researchers have extensively studied various methods of FFRs decontaminant in recent years. The pandemic of COVID-19 generates a great demand for the FFRs, thus suitable decontamination method is important to be identified. There is little attention has been paid to compare the performance of chemical decontamination method using FFRs produced by different manufacturers. This study is carried out to evaluate the effectiveness of three chemical decontamination methods; IPA, VHP and detergent. The performance of the FFRs after decontamination was measured by aerosol penetration and average filter resistance. Face mask type N95 and KN95 with four different models were used in the study.

2. Material and Methods

2.1. Respirator Selection

Four respirator models were used in this study, of which we referred as Model 1, Model 2, Model 3 and Model 4. Model 1 and Model 2 FFRs are approved by the USA-NIOSH while Model 3 and Model 4 FFRs are approved by the China-NIOSH. Figure 1 shows the four FFRs models used in the analysis. FFRs Models 1 and 2 are N95, and Models 3 and 4 are KN95. Table 1 shows description of the Models 1, to 4 used in the study. All FFRs consist of 3 layers with thicknesses ranging from 1.11 to 2.90 mm.

| Model | Manufacturer | Thickness (mm) | Layers | Filter | Shape        |
|-------|--------------|----------------|--------|--------|--------------|
| 1     | Singapore    | 2.90           | 3      | Melt blown | Fold valve less |
| 2     | China        | 2.47           | 3      | Melt blown | Fold valve less |
| 3     | China        | 1.11           | 3      | Melt blown | Fold valve less |
| 4     | China        | 1.83           | 3      | Melt blown | Fold valve less |
Figure 1. Four FFRs models considered in the experimental; (a) Model 1, (b) Model 2, (c) Model 3 and (d) Model 4

2.2. Decontamination Method Selection

Three chemical decontamination methods were used in the study: Isopropyl Alcohol (IPA), vaporized hydrogen peroxide (VHP) and detergent. Table 2 summarizes the experimental conditions and parameters for the three decontamination methods. All laboratory experiments were conducted under standard laboratory conditions (22 ± 2 °C and relative humidity of 50 ± 10%) on triplicate sets of FFRs. The test conditions of the three decontamination methods are selected based on previous study reported by Visscheri et al. [7]. The conditions were generally recommended by the literature and it was reported as effective conditions for the three decontamination techniques.

| Decontamination method | Recommended concentration /property | Recommended effective contact time | 1st test condition Less aggressive | 2nd test condition More aggressive |
|------------------------|------------------------------------|----------------------------------|-----------------------------------|----------------------------------|
| IPA                    | 70%                                | 10 to 30 min.                    | Dunk 1 second                     | Dunk 2 min.                      |
| VHP                    | 58%                                | 28 min.                          | 1 cycle/36 min.                   | 5 cycle/180 min.                 |
| Detergent              | 1 g/liter                          | 2 min.                           | 2 min.                            | 20 min.                          |

Control or 'as-received' sample refers to the untreated out-of-the-box FFRs for the four FFRs models used in the analysis. Liquid chemical treatment solutions were made by appropriate dilutions with tap water and reagents: IPA, 70%; Breeze detergent, 1g/L and diluted in tap water. FFRs samples were placed (submerged) into a pail containing 1 liters of treatment solution. FFRs were removed, hung on and air-dried for 72 hours, prior to filter penetration testing. For VHP, all samples were put in to the Plasmapp Sterlink Low Temperature Plasma Sterilizer for 2 stage cycle (1 cycle and 5 cycles). The respirators were air-dried 72 hours before filtering.

2.3. Experimental Design

A series of experiments were conducted on two N95 and two KN 95 FFRs model using the three decontamination methods described in Table 2. Two different conditions were considered in the study, which are chemical concentrations and time lengths. Control sample refers to the untreated out-of-the-
box FFRs or no decontamination. At least three samples were used in airflow resistance and filter aerosol penetration tests, and the average was recorded.

The TSI 8130 instrument available at the National Institute of Occupational Safety and Health (NIOSH) Malaysia was used to identify the performance of the FFRs after decontamination process. The 72-hour air drying time was performed after decontamination to make sure the sample totally dry before penetration test. A visual inspection was done after decontamination to detect any noticeable changes in the respirator (e.g., straps, nose clips, exhalation valves, etc.), in addition to the filtering results.

2.4. Characterization

TSI Model 8130 Automated Filter Tester (AFT) (TSI, Inc., St. Paul, MN) was used to measure filter aerosol penetration and airflow resistance. The TSI 8130 delivers a solid polydisperse sodium chloride (NaCl) aerosol which meets the particle size and size distribution criteria set forth in 42 CFR 84 Subpart K, Section 84.181.(g) for NIOSH certification (CFR, 1995). The TSI Model 8130 AFT produces a particle concentration of 12 - 20 mg/m³ and generates an initial instantaneous filter penetration result. The NaCl aerosol must have a count median diameter (CMD) of 0.075 ± 0.020 micrometer and a geometric standard deviation (GSD) not exceeding 1.86.

3. Results and Discussion

Table 3 shows the average aerosol penetration results. For comparison purpose, normalized data for all the decontamination methods for Model 1 to Model 4 are presented in Figure 2 (a-c). The normalized data was calculated based on the average filter aerosol penetration performance of each of the FFRs divided with that of control FFRs sample. Comparison on the control samples showed that Model 1 exhibited the lowest average filter aerosol penetration value than those other FFRs. Low average filter aerosol penetration value is required based on 95% filtration efficiency for N95 and KN95 FFRs. It is interesting to note that the thickness of the FFRs does not influence the filter aerosol penetration performance. This is proven by the inconsistency data shown by the FFRs models. Based on the data for IPA decontamination method, FFRs Model 4 showed good properties with the lowest normalized aerosol penetration values while Models 1, 2 and 3 showed higher values. This indicated FFRs Model 4 exhibited less deviation from the control FFRs. As expected, increase in soaking time results in increasing average filter aerosol penetration due to the filter structure degradation of the FFRs.

For VHP decontamination method, Model 2 and Model 3 showed the lowest normalized aerosol penetration values after sterilized for 1 cycle in 58% concentration. This indicated that less degradation of the filter structures was occurred in these two models compared to those Models 1 and 4. FFRs Model 3 which was decontaminated with detergent showed the lowest normalized aerosol penetration for test condition of 2 minutes, and the value increased for the 20 minutes test condition.

The increased of the normalized data for filter aerosol penetration trends shown in Figure 2 (a-c) was possibly due to the changes in the density and/or spatial distribution of the electret charges on the surface of the polymer fibres by the liquid phase application [11]. Based on the normalized data for the three decontamination methods, VHP is the most promising method since the normalized values observed were less than 5.2 compared to those 2 methods.
Table 3. Average filter aerosol penetration results of four types of face masks using IPA, VHP and detergent methods (note: in the bracket is the normalize value).

| Decontamination method | Test condition | Type of Face Masks |
|------------------------|----------------|--------------------|
| IPA                    | Control        | 0.181 (1)          |
|                        | Dunk 1 Sec     | 7.92 (43.7)        |
|                        | Dunk 1 min.    | 8.91 (49.2)        |
| VHP                    | Control        | 0.181 (1)          |
|                        | 1 Cycle        | 0.437 (2.4)        |
|                        | 5 Cycle        | 0.401 (2.2)        |
| Detergent              | Control        | 0.181 (1)          |
|                        | 2 min.         | 7.35 (40.6)        |
|                        | 20 min.        | 41.6 (229.8)       |

Figure 2. Normalized data of average filter aerosol penetration using decontamination (a) IPA, (b) VHP and (c) Detergent

Table 4 shows the average filter air flow resistance results and Figure 3 (a-c) shows normalized data for all the decontamination methods for Models 1 to 4. Results shown by the control samples indicated that Model 1 exhibited the lowest average filter air flow resistance value than those other FFRs. Low average filter air flow resistance value is desirable and indicates better performance of the FFRs. Based
on the data in Table 4, it is found that insignificant changes were observed for the airflow resistance values using the three decontamination methods. Data shown by the normalized values in Figure 3 (a-c) indicated the small changes in the filter resistance performance.

Table 4. Average filter airflow resistance results of four types of face masks using IPA, VHP and detergent methods (note: in the bracket is the normalize value)

| Decontamination method | Test condition | Type of Face Masks |
|------------------------|----------------|-------------------|
|                         |                | Model 1 (mmH₂O)   | Model 2 (mmH₂O) | Model 3 (mmH₂O) | Model 4 (mmH₂O) |
| IPA                    | Control        | 8.7 (1)           | 13.3 (1)        | 12.6 (1)        | 10.0 (1)        |
|                        | Dunk 1 Sec     | 9.9 (1.14)        | 13.4 (1.01)     | 12.2 (0.97)     | 10.1 (1.01)     |
|                        | Dunk 1 min.    | 9.0 (1.03)        | 12.1 (0.91)     | 12.5 (0.99)     | 10.3 (1.03)     |
| VHP                    | Control        | 8.7 (1)           | 13.3 (1)        | 12.6 (1)        | 10.0 (1)        |
|                        | 1 Cycle        | 9.5 (1.09)        | 14.7 (1.11)     | 12.9 (1.02)     | 8.3 (0.83)      |
|                        | 5 Cycle        | 8.5 (0.98)        | 11.7 (0.88)     | 11.8 (0.94)     | 11.0 (1.1)      |
| Detergent              | Control        | 8.7 (1)           | 13.3 (1)        | 12.6 (1)        | 10.0 (1)        |
|                        | 2 min.         | 9.7 (1.11)        | 12.7 (0.95)     | 7.6 (0.60)      | 10.3 (1.03)     |
|                        | 20 min.        | 8.4 (0.97)        | 14.3 (1.08)     | 8.6 (0.68)      | 9.0 (0.9)       |

Figure 3. Normalized data of average airflow resistance using decontamination (a) IPA, (b) VHP and (c) Detergent
4. **Conclusions**

Based on the results of chemical decontamination methods used for four types of FFRs, the following conclusions were made:

(a) Comparison on the control samples, Model 1 exhibited the lowest average filter aerosol penetration and average filter air flow resistance than those other FFRs.

(b) Based on the normalized data for filter aerosol penetration of the three decontamination methods, VHP is recommended to be used for decontamination methods for FFRs.

(c) Model 3 FFRs showed less deviation in the normalized filter aerosol penetration and normalized filter air flow resistance for the three decontamination methods.

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