Dry heat as a decontamination method for N95 face respirator reuse

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Graphic TOC
Abstract

A pandemic such as COVID-19 can cause a depletion of face respirators throughout the world, forcing temporal respirator reuse. In this research, dry heat was systematically evaluated by decontamination, filtration performance, and qualitative fit testing to help safe reuse of N95 (1860, 3M) respirators. As a result, the dry heat generated by a cooker (120°C, 50 min) was effective in inactivating >4.7 log viruses without deteriorating its intended functions. Therefore, we suggest the dry heat generated by a pressure cooker (such as rice cookers and instant pots) as a reliable and accessible decontamination method for the N95 face respirator reuse.

1. Introduction

An N95 face respirator is one of the essential personal protection equipment (PPE) during the outbreak of contagious disease. Although the respirator is supposed to be disposable, high demand for the respirator in a pandemic, such as COVID-19, can force the healthcare workers to reuse the respirator. The issue of respirator shortage has been reported since this pandemic started spreading in the US\(^1\). The respirator shortage was also reported at healthcare facilities in the US during the 2004 SARS, and the 2009 H1N1 influenza outbreak and Center for Disease Control and Prevention (CDC) temporality recommended extended use and limited reuse of the respirators to address the respirator shortage\(^2\). The primary problem of extended and limited reuse is that once the respirators are contaminated, they can play a role as a potential transmission route of pathogens to not only patients but also the healthcare workers. Since the safety of the healthcare workers is a priority to deal with the pandemic, the extended use and limited reuse have to be implemented after decontamination of the pathogens is performed\(^3\).

The challenges of decontaminating an N95 respirator arises from the following five requirements. First, the decontamination treatment has to prove virucidal activity in realistic experimental conditions. For example, Food and Drug Administration (FDA) requires the verification of decontamination (>3 log virucidal efficacy) should be performed with the
pathogens in soiling agents (e.g., blood, mucus, or sebum). Furthermore, we found that the different characteristics of the respirator should be considered for experimental design. For instance, the N95 respirator widely used in the hospitals (1860, 3M) consists of two different surface materials facing the atmosphere (hydrophobic) and the wearer (hydrophilic). This hydrophilic surface immediately absorbs solutions such as saliva and can protect the pathogens from disinfectant. We discovered the above conditions significantly affect inactivation efficacy and were not considered in the previous studies. Second, the filtration performance (filtration efficiency and breathability) should not be affected by the decontamination process. Third, the treated respirator must provide a tight fit to the wearer’s face. Fourth, harmful chemicals should not exist in the respirator for the wearer’s safety. Finally, users should easily access decontamination technology.

Dry heat has the potential of satisfying the above five requirements. Heat is one of the most conventional disinfection technologies, so the thermal inactivation efficacies for various pathogens are available. Also, the dry heat was recognized as a decontamination technology with minimal impact on the respirator. In addition, we can easily find appliances generating heat, such as a rice cooker and an instant pot. However, no experimental conclusions about dry heat have been made for the N95 respirator reuse in terms of these five requirements. In this research, we conducted experiments for decontamination, filtration performance, and fit-test. Based on the results, we suggest dry heat as an appropriate decontamination technology for the N95 respirator reuse.

2. Materials and method

2.1. Materials

2.1.1. Respirator and cooker
N95 face mask respirators (1860, 3M) and a pressure cooker (WM-CS60004W, Farberware), which is inexpensive and easily accessible in a market, were used for this research. The pot is
22 cm in diameter and 15 cm in height, and 5.7 L in volume so that it can accommodate three respirators in one layer and three layers in a pot. If the respirators are stacked up, about 20 respirators can be treated at the same time. The surface temperatures of the pot and the respirator were measured every 5 to 13 min during the dry heat treatment using an infrared thermometer (IRT205, General Tools).

2.1.2. Surrogate virus

Tulane virus was used as a surrogate virus, which was received from Cincinnati Children’s Hospital Medical Center\(^\text{10}\). Although SARS-CoV-2 virus (enveloped, 30 kb genome length, 50-200 nm diameter) is different from Tulane virus (non-enveloped, 7 kb genome length, 40 nm diameter) in terms of viral structure\(^\text{11}\), Tulane viruses can be a proper surrogate for our research purpose because they are known to be more heat-resistant (1.74 min at 56°C\(^\text{12}\)) than SARS-CoV (0.86 min at 56°C) and MERS-CoV (about 1 min at 56°C\(^\text{13}\)). The initial concentration of about 10\(^7\) PFU/mL was prepared in 1 mM NaCl and 0.1 mM CaCl\(_2\) solution using an ultracentrifuge. Decontamination efficacy was determined by plaque assay using the MA104 cell line. Detailed information for the virus is described in our previous work\(^\text{14}\). The virus suspension was mixed to artificial saliva with a 1:1 ratio before use. The artificial saliva was prepared as a soiling agent following ASTM E2720-16 with slight modification (Table 1S). All the experiments were replicated three times.

2.2. Methods

2.2.1. Decontamination test

A volume of 30 µL of each testing solution was put on five locations of the respirator (inside edge, inside center, outside edge, outside center, and strap). Each side of the respirator has hydrophilic and hydrophobic characteristics. As a result, the testing solution was absorbed by the hydrophilic surface (facing a wearer) while a droplet formed on the hydrophobic surface.
The respirator was left in a biosafety cabinet until through evaporation (about 1-2 hours) to mimic the condition when the respirators were used. The contaminated respirator was put on the center of the cooker and 5 cm above the bottom surface using a bunch of tissue (Fig 1S) followed by one cycle of dry heat (120°C for 50 min). The treated respirator was cut into pieces and put in the culture medium. The viruses were detached from the respirator fragments by 3 min vortex and 30 min shaking at 450 rpm. The same procedure was performed without the dry heat treatment for a negative control. The detachment efficiency from each side of the respirator was confirmed to be about 23% (Fig. 2S). The supernatant was used for plaque assay to determine decontamination efficacy by the dry heat.

2.2.2. Filtration performance test

The particle filtration efficiency test of the filters was performed using a slightly modified version of the NIOSH 42 CFR 84 regulations\textsuperscript{15}. The detailed experimental setup and procedure are provided in Fig 3S.

Briefly, a small portion (47 mm diameter) of the N95 mask fabric was cut and loaded onto a 47 mm filter holder (URG, Carrboro, NC, USA). 2% NaCl solution (which is commonly used for measuring the penetration efficiency of N95 masks\textsuperscript{15}) was aerosolized using a constant output atomizer (TSI Model 3076, MN, USA). The polydisperse NaCl aerosols generated from the atomizer were first dried and charge neutralized; after which it was passed into a polypropylene chamber, which houses the filter holder. We used a condensation particle counter (CPC, TSI Model 3022A; flow rate = 1.5 lpm) to measure the particle concentration before and after loading the test filter (i.e., a section of the mask) in the filter holder. While NIOSH recommends using an 85 lpm flow rate for testing N95 masks, which results in an equivalent face velocity of 9.4 cm/s, we tested the filters for 2 face velocities: 9.4 and 17.3 cm/s. A pressure gauge (Magnehelic 1-10 inches of water) was also connected in parallel, right downstream of the filter-holder using a T-
connecter to measure the pressure drop across the mask. The particle number concentration was measured before and after connecting the filter holder, and particle removal efficiency of the mask was measured by the following equation:

$$\text{Particle removal Efficiency (\%)} = \left( 1 - \frac{\text{particle number concentration after placing the mask (\#/cm}^2\)}{\text{particle number concentration before placing the mask (\#/cm}^2\)} \right) \times 100$$

2.2.3. Qualitative Fit-testing

Qualitative fit-testing was performed (1910.134 App A, OSHA) using a fit test kit (FT-30, 3M™) in order to check the overall integrity of the respirators. In brief, the respirators treated by the cooker for different decontamination cycles (1, 2, and 3) were prepared together with the negative control. A test taker donned each respirator and the hood was placed over the head. The fit-test solution (Bitrex) was provided every 30 seconds into the hood using a nebulizer so Bitrex was aerosolized in the hood throughout the test. The task taker performed the following missions for 1 min each; normal breathing, deep breathing, turning head side to side, moving the head up and down, talking, bending over at the waist or jogging in place, and finally normal breathing. If the test taker tastes the Bitex at any time, the test fails.

3. Results

3.1. Decontamination efficacy

The cooker provided dry heat by heating the pot surface. The temperature of the pot surface was rapidly increased to 170°C within 5 min and fluctuated between 120°C and 150°C to hold the temperature inside of the pot (Fig 1a). Therefore, the respirator temperature also increased to
its target temperature in 15 min, and the respirator was maintained at 110-120°C throughout one complete cycle of dry heat treatment (Fig. 1a).

Dry heat was effective in inactivating the viruses spiked into the artificial saliva in the respirator. The inactivation rate increased dramatically once the respirator reached the target temperature. For example, the dry heat achieved 3 log reductions within 30 min, and it also showed more than 4.7 log reduction by the one cycle treatment (Fig. 1b). The inactivation rates were similar, regardless of inoculation locations. This result meant that the dry heat was evenly transferred into the respirator, and the viruses were inactivated without being influenced by the respirator shape.

![Fig. 1 Effect of dry heat treatment on (a) temperature profiles for the surfaces of pot and respirator and (b) virus inactivation rate. The asterisks over the virus inactivation rate indicate the detection limit.](image)

### 3.2. Filtration performance

The integrity of filtration performance is crucial for respirator reuse. We conducted two types of experiments to prove the integrity of the respirator; filtration efficiency and pressure drop. As shown in Fig 2, the initial particle filtration efficiency of the new mask was >99% at a face
velocity of 9.4 cm/s, and 98% at 17.3 cm/s. After 3 cycles of rice cooker decontamination, particle filtration efficiency was still above 95% (i.e. 97% at 9.45 cm/s and 95% at 17.3 cm/s). The pressure drop across the mask was also not significantly affected by the decontamination process, as evident from Figure 2b. Collectively these results suggest that the rice cooker decontamination process does not compromise the integrity of the filter material even after three cycles of dry heat treatment.

Fig 2. Effect of rice cooker decontamination on (a) the particle filtration efficiency and (b) pressure drop across the filter. The horizontal dashed line in (a) shows the 95% particle filtration efficiency requirement for N95 masks. The face velocity of 9.4 cm/s is equivalent to NIOSH recommended the most severe breathing flow rate of 85 lpm. All the experiments were repeated thrice. The error bars denote the standard deviation (1σ) of the triplicate measurements.

3.3. Fit-test using Bitrex
A test taker’s sensitivity for Bitrex was 10. The test taker did not taste any bitrex throughout the qualitative fit-testing. Therefore, all the masks treated by the dry heat through different decontamination cycles (i.e., 0, 1, 2, and 3) passed the Bitrex test. In addition, no visible deformations (such as burning signs, nose form detachment, elasticity loss of band, or deformation of the entire shape) except for ink spread (Fig. 4S) were noticed on the respirator after three cycles of the dry heat.

4. Discussion
We designed strict conditions for decontamination experiments to demonstrate the worst-case scenario for the respirator contamination (a heat-resistant surrogate virus, soiling agent, various inoculation sites, and through evaporation). The dry heat generated by the cooker satisfied the requirements for the N95 respirator reuse showing >4.7 log virus without compromising its function (filtration performance and fit-test). This result is conservative enough to be used to cope with SARS-CoV-2, considering the estimated times for 6-log reduction of SARS-CoV-1 and MERS-CoV by dry heat (120°C) were within 1 min\(^7\). Although the maximum operating temperature for the respirator is 50°C, according to the manufacturer\(^16\), the respiratory function was not significantly affected. This can be explained by the fact that the primary materials for the respirator are polyester, polypropylene, polyurethane, polyisoprene\(^16\), which can withstand a temperature as high as 150°C\(^17,18\). Note that the temperature of the pot surface is higher than the allowable temperature for the outside surface of the respirator (polypropylene), so the direct touch must be avoided using a holder playing the role of an insulator (such as tissue shown in TOC and Fig. 1S). It was reported that N95 was melted by dry heat generated by an oven (Isotemp 500 Series, Fisher Scientific)\(^19,20\). However, they placed the respirator on a metal pan, which caused direct heat conduction. We confirmed that the heat radiation by the oven (120°C) for 24 hours could not melt the respirator surface.
The dry heat can be advantageous to other suggested treatments\textsuperscript{21}, which were screened out by our preliminary experiments. In the case of UV irradiation, for example, the disinfection efficacy dramatically decreased when the soiling agents were added to viruses, and the UV irradiation did not work at all when the virus solution was penetrated the hydrophilic surfaces. It was presented that the virus inactivation using UV irradiation was significantly affected by the respirator materials\textsuperscript{22}. We also confirmed that the inner nose cushion was easily separated after the moist heat was applied to the respirator. A similar observation was made previously\textsuperscript{23}. Hydrogen peroxide vapor has been considered as an alternative solution for reusing respirators\textsuperscript{6}. However, complex facilities such as a separate room equipped with gas injection and ventilation system could hinder the method to be widely used in small scale facilities\textsuperscript{24}.

Our results showed that a conventional pressure cooker, such as the one shown in the TOC, can be used to decontaminate the N95 respirators for reuse at least three times. The temperature and treatment time would be different depending on the heating devices, so the specification should be considered to select the proper devices, or the users can monitor the temperature of their appliances using an infrared thermometer. However, we believe that any device which provides dry heat holding the respirator temperature at 120°C for 30 min would work. Rice cookers and instant pots are the ideal appliances because they provide proper temperature with the respirator uniformly. Baking ovens and air fryers would not be appropriate because of a much higher working temperature (156-168°C) than the melting point of the mask materials\textsuperscript{18}.

We recommend dry heat treatment of 120°C for 50 minutes is an appropriate method for the N95 respirator (1860, 3M) reuse. Further studies for other types of respirators reuse are needed because different materials may require different temperature and treatment time to draw the same conclusion.
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