Applying Heat and Humidity using Stove Boiled Water for Decontamination of N95 Respirators in Low Resource Settings

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Abstract: Global shortages of N95 masks have led to an urgent need of N95 decontamination and reuse methods that are scientifically validated and available globally. Although several large scale decontamination methods have been proposed (hydrogen peroxide vapor, UV-C); many of them are not applicable in remote and low resource settings. Heat with humidity has been demonstrated as a promising decontamination approach, but care must be taken when implementing this method at a grassroots level. Here we present a simple method to provide stable humidity and temperature for individual N95 masks which can be simply scaled in low resource settings. Moist heat (>50% humidity, 65-80°C temperature) was applied to Kimberly-Clark N95 respirators for over 30 minutes by placing sealed containers with N95 respirators into water that had been brought to a rolling boil and removed from heat, and then allowing the containers to sit for over 45 minutes. After rising to their threshold points, temperature and humidity remained above 65°C and 50% for a treatment time of at least 30 minutes. Filtration efficiency of 0.3-4.99µm particles remained above 97% after 5 treatment cycles across all particle size sub-ranges, which is consistent with previously-reported data for similar heat and humidity conditions on different N95 FFR models. Although no fit tests were conducted on these masks after treatment, prior data on moist heat based treatment indicates consistent fit for up to five cycles of decontamination. This method of applying heat and humidity for the purpose of N95 respirator decontamination can be implemented on open flame stoves for low resource settings without reliable electricity access or where other methods of decontamination are not accessible. Higher temperatures or longer treatment times, such as treatment at >70°C for over 30 minutes, could be achieved by increasing the volumes of boiled water used. Although fresh N95 masks should always be used - whenever available - we believe this simple yet reliable method provides a low cost, electricity free method for N95 decontamination in remote parts of the world.
INTRODUCTION

The ongoing COVID-19 pandemic has caused a worldwide shortage of N95 filtering facepiece respirators (FFRs). Many health facilities are rationing N95 FFRs and reusing them with various decontamination protocols. Nations with emerging economies and high population densities (e.g. India, Pakistan, Bangladesh, Brazil, Peru, Ecuador), are expected to face significant public health challenges due to these shortages. Therefore, it is important to develop accessible procedures for decontamination and re-use of N95 FFRs without damaging their fit or filtration efficiency.

At a minimum, decontamination requires inactivation of the SARS-CoV-2 virus and maintenance of the fit and filtration efficiency of the N95 respirator. Temperature treatments, which can inactivate viruses through protein denaturation, represent a potential disinfection method [1]. While there is recent data suggesting that SARS-CoV-2 in liquid media can be inactivated by exposure to 70°C for 5 minutes [2], it appears that the virus requires a much longer heat-treatment for inactivation on N95 FFR surfaces. A recent, non-peer-reviewed report indicates that application of 70°C dry heat for 30 min only led to a 1.9-log reduction in viral load of SARS-CoV-2 in an unknown media on N95 fabric [3], which is below the minimum 3-log inactivation level suggested by the FDA for emergency use authorization for decontamination [4]. While the same study found that 70°C for 60 minutes was sufficient for inactivation on N95 fabric, it was not sufficient for inactivation on steel surfaces, indicating that the N95 nosepiece may remain contaminated. Additionally, the media used for inoculation may not have included mucin or other proteins that can stabilise viral particles in a real-world setting [5, 6]. Recent non-peer-reviewed data also suggests that the inoculation media may dramatically affect inactivation of viruses by dry heat treatment, indicating that 70°C dry heat may not provide a safety margin for viral inactivation [7]. While direct studies involving the effects of heat and humidity on the SARS-CoV-2 virus on N95 FFRs are limited, increased humidity was found to increase inactivation rates of the H1N1 influenza virus at 65°C on steel surfaces [8-10]. A non-peer-reviewed report found that increasing relative humidity from ~8% to ~62-66% increased inactivation of MS2 and Phi6 viruses on N95 FFRs by >4log(10) during a combination heat/UV treatment [7]. Therefore, it seems possible that increasing the temperature, humidity, and/or duration of decontamination above the previously-studied 60 min at 70°C dry heat will lead to sufficient inactivation of SARS-CoV-2 on an N95 FFR.

While increasing temperature and humidity may improve viral inactivation, it also carries the risk of damaging N95 fit and filtration. Several N95 FFR models have been shown to fail fit tests after greater than one 121°C autoclave treatment cycle, indicating that temperature, humidity, and duration of decontamination must be carefully chosen to strike a balance between viral inactivation and N95 performance [11]. Fortunately, many models of N95 FFR have been shown to undergo at least one cycle of elevated temperature (65–85°C) at greater than 50% relative humidity for 20–30 min while maintaining filtration efficacy and fit [12, 13, 14], indicating that conditions of moist heat at 65-80°C, with 50% relative humidity for 30 minutes may be a promising target for decontamination of SARS-CoV-2 on N95 FFRs. However, reliably achieving these heat and humidity conditions in low resource environments is challenging, particularly...
those without equipment for heating or stable access to electricity. Equipment typically used for surgical sterilisation (e.g. autoclaves) run at temperatures which, as outlined earlier, may result in a loss of fit and filtration efficiency [12,13]. There is a need to develop methods applicable to low resource contexts that can achieve 65-80°C temperatures at high humidity (>50%) for over 30 minutes. A method of heating N95 FFRs with moisture to achieve temperatures of 85°C at 65-80% humidity was recently implemented by placing plastic containers containing N95 FFRs and 500uL of water into an oven [14]. Implementation of a similar method involving equipment available in low resource settings could have wide applicability.

Open flame stoves are widely used for cooking in a range of remote and low resource contexts where access to electricity is limited or intermittent. Using these stoves to achieve heat and humidity conditions could lead to a widely accessible method of decontamination, if validated properly. Boiling water and cooking utensils are commonly used across India, Bangladesh, Pakistan and many other countries to disinfect surgical equipment in clinical settings lacking traditional autoclaves [15-17]. Regulation of the temperatures inside a cooker or closed cooking vessel could be achieved through the use of high thermal mass elements such as boiling water. Heating of the water to its boiling point at atmospheric pressure provides a reliable way of reaching a set temperature. Due to the high heat capacity of water, heat transfer may occur at slow enough rates to maintain 65-80°C temperatures and >50% humidity for over 30 minutes after the vessel is removed from the stove.

Here we implement a method in which N95 respirators are placed inside containers, which are placed inside larger cooking vessels with water that has been heated to a rolling boil and then removed from heat. We demonstrate that this method can maintain a consistent elevated temperature and humidity as required for decontamination of N95 FFRs using materials available in low-resource settings. This method could be implemented using a wide variety of conditions based on practical considerations and the materials available in a local context. We implement this method using a 1.65L Pyrex glass container as the FFR holding container, saturation of a 5x5cm paper towel with water from a tap, and a standard 6 quart (5.7L) cooking vessel containing 2L of water as the larger vessel.

HEATING PROTOCOL

1. A Kimberly Clark N95 respirator was placed in a 1.75 quart (1.65L) Pyrex container (Figure 1a).
2. A small strip of a paper towel (~5x5cm before folding) was folded, doused in water under a tap, squeezed to remove excess water until it no longer dripped passively and then placed in the Pyrex mask container. The container was closed with a tight lid. A BME280 sensor (Sparkfun Inc) was included in the container to log temperature and humidity data. For testing purposes, the respirator was separated into two halves to obtain two filtration data points during the same treatment cycle (Figure 1b). During implementation of this protocol, the N95 mask should be minimally handled.
3. 2L of water was brought to a full rolling boil inside a separate, larger 6 quart (5.7L) vessel, and the vessel was then removed from heat. It is important to clarify that a
rolling boil, where large bubbles vigorously rise and continually break the surface, was achieved, as opposed to a simmering boil, where small bubbles occasionally break the surface. We turn on logging of testing data from this time point onwards. While this occurred on an electric stove, this method generalises to open flame stoves. The presence of bubbles rapidly breaking the surface was used as a visual marker for boiling, which, neglecting major changes in altitude, reliably indicates water temperatures of close to 100°C. Water temperatures measured (Kizen Instant Read Meat Thermometer) after moving the vessel off the stove ranged from 93-97°C.

4. The sealed respirator container was immediately placed in the large vessel containing the boiled water (Figure 1c).

5. The large vessel was covered with a non-airtight lid and allowed to sit with the closed respirator container inside for at least 45 minutes (Figure 1d).

6. The container was first removed from the large vessel and then opened.

**Figure 1:** (a) Kimberly-Clark N95 respirator inside 1.65L (7 cup, 1.75 quart) container, (b) Folded 5x5cm wet paper towel, two halves of the respirator and BME280 sensor inside the container (c) Large 5.7L cooking vessel, removed from stove after heating 2L water to vigorous boil, with a closed 1.65L Pyrex container respirator floating inside, (c)Vessel covered with a plate and allowed to sit for at least 45 minutes while data is logged.
Temperature and humidity inside the container were measured with a BME280 sensor (Sparkfun Inc) and logged with an Arduino Uno. They are reported in Figure 2.

![Temperature and Humidity Graph](image)

**Figure 2:** Temperature and humidity inside the container holding N95 respirators during the 5 treatment cycles after which they underwent filtration testing. Rapid decrease in humidity in the end is due to opening of the container at the end of the decontamination treatment.

The minimum temperature target of 65°C was typically reached after approximately 4-7 minutes and max temperatures of between 75-80°C were observed. The initial spike in humidity is due to saturation of air with water vapour at low temperatures, followed by a rapid increase in vapour pressure (and hence decrease in relative humidity) upon heating, followed by a gradual increase in humidity as the water in the sealed container evaporates. The rapid drop in humidity occurs when the container is opened at the end of treatment. The minimum humidity target was reached between 10-13 minutes after testing began and consistently reached a maximum of ~60%. The variance in data is partly caused by slight differences in time taken to move the container into the large vessel after removing from boil, water volumes, average water temperature at the end of the boil, precise amount of liquid soaked into the towel and in data logging start time. These are likely to occur during normal implementation of this method in any low resource setting.

Despite these operating variations, across all trials the humidity and temperature remained simultaneously above the minimum targets (after reaching both the 50% humidity and 65°C temperature targets) or over 30 minutes. Running the treatment for 45 mins would allow the system to rise to the targets and then maintain them for 30 minutes.
**FILTRATION EFFICIENCY**

![Image of N95 mask and particle counter](image)

**Figure 3**: Filtering efficiency test setup to test filter efficiency of a N95 mask using LightHouse handheld particle counter to detect particles of size 0.3 µm - 10 µm produced by burning an incense stick.

A simple experimental test rig (Figure 3) and method was used to test the particle filtration efficiency of various materials including N95-grade masks. The setup includes a LightHouse handheld particle counter (Model 3016 IAQ), Incense: Satya Sai Baba Nag Champa 100 Gram, and connectors (universal cuff adaptor, teleflex multi-adaptor). The detector measures particles at an airflow rate of 2.83 L/min. The incense produces particles of various sizes, including those in the range picked up by the detector (0.3 µm - 10 µm). We first measure the number of particles produced by the incense. Then, we place the filter on the setup and run the particle counter to measure the number of unfiltered particles (note the incense is moved back the length of the filter mount away from the original position to maintain similar incense emission).

To calculate the filtration efficiency, we calculate the ratio of unfiltered particles to the number of particles produced by the incense, and then subtract from one. The filter efficiencies tested for Kimberly Clark N95 masks after repeated heating cycles, for particles sized 0.3-04.99 µm, are reported below in Figure 4. Filtration efficiency after 5 treatment cycles for particle sizes after 5 treatment cycles are reported in Table 1. Note the filter efficiency testing is done using a simple in house experimental setup as opposed to the standard testing which typically uses the TSI Automated filter tester 8130A.
**Figure 4:** Filtering efficiency of particles sized 0.3-4.99 μm, at an intake rate of 2.83 l/min, of Kimberly Clark N95 respirators undergoing cycles of heat treatments using the method detailed in this protocol with 2L of boiled water.

**Table 1:** Filtering efficiency of particles for different particle sizes after the 5th treatment cycle.

| Particle Size (microns) | Filtration Efficiency (%) |
|-------------------------|----------------------------|
| 0.3-0.49                | 97.99 ± 0.38               |
| 0.5-0.99                | 98.16 ± 0.33               |
| 1.0-2.49                | 98.57 ± 2.45               |
| 2.5-4.99                | 100 ± 0.0                  |
EFFECT OF CHANGING WATER VOLUME

It may be desirable to achieve time and temperature parameters greater than 65°C for 30 minutes. A change in the dimensions of containers or water volumes used in the system will result in a change in the maximum temperature, and the time spent at that temperature. In particular, the cooling rate of the system is dependent upon the large vessel surface area to water volume ratio where the higher the surface area to water volume ratio, the higher the cooling rate. The effect of increasing boiled water volume to 3L while maintaining vessel sizing is shown in Figure 5a. This test was carried out without FFRs. The maximum achieved temperature increases along with time spent at a given temperature. However, as the vapour pressure is higher at those higher temperatures, it takes longer to reach the required relative humidity, and the humidity reached is lower (10 minutes to achieve 50% for 2L vs 17 minutes for 3L). This could be adjusted by increasing the size or number of soaked folded paper towels included in the FFR container.

The time spent simultaneously above a temperature threshold (65°C or 70°C) and the humidity threshold of 50% is plotted for 2L and 3L boiling volumes in Figure 5b. Use of 3L boiled water would allow for 70°C moist heat to be applied for over 30 minutes, or 65°C moist heat to be applied for almost 60 minutes.

Figure 5a (left): Temperature and humidity inside the container over a single long cycle when placed in a vessel with 2L boiled water (solid lines) and 3L boiled water (dotted lines with circular markers). Figure 5b (right): Time spent simultaneously above both humidity (50%) and temperature (65 & 70°C) thresholds for 2L and 3L boiled water volumes.
LOWERED FILTRATION EFFICIENCY AFTER TREATING N95 RESPIRATORS IN ZIPLOC BAGS

It is desirable to consider how this method could be implemented using other materials based on local availability. A variant of this method was implemented using a smaller vessel (a 2.5L pressure cooker), with 1.5L water volume, where Ziploc bags were used to hold the respirators instead of the large Pyrex container. To avoid having the Ziploc directly contact the boiling water, they rested in an open steel saucepan floating in the water.

![Figure 6: (a) Kimberly Clark N95 respirator inside a ziploc bag with a wet folded 5x5cm paper towel, (b) Ziploc bag with respirator resting on steel saucepan inside pressure cooker holding boiled water after being taken off stove](image)

As previously, a 5x5cm folded wet paper towel was placed inside the Ziploc bag along with the respirator halves (Figure 6a) and the sensor. Water in the open pressure cooker was brought to a boil and removed from heat. The Ziploc bag, resting in a steel saucepan, was immediately placed in the pressure cooker (Figure 6b), which was then sealed and allowed to sit for 45 minutes. It was noted during implementation that this procedure that it was challenging to reliably keep the moist towel and associated water droplets separate from the respirator, representing a risk of filtration piece getting wet, which could affect filtration efficiency. While temperature and humidity targets were reached, filtration efficiency of one of the respirator halves was measured to be below 95% after cycle 3 (Figure 7).
Figure 7: Filtration efficiency of particles sized 0.3-4.99 μm at an intake rate of 2.83 l/min as outlined previously, undergoing cycles of heat treatments while placed in Ziploc bags.

This indicates that holding N95 respirators in Ziploc bags while implementing this method creates a risk of filtration efficiency being reduced to below 95%. Because of this - we do not recommend the use of zip-lock bags for decontamination. Ziplock bags might allow for contact between N95 mask and water droplets in the bag - leading to lowering of filtration efficiency.

CONCLUSIONS
Here we demonstrate a highly accessible heating protocol for N95 respirators that achieves 65°C and 50% humidity for over 30 minutes without any advanced instrumentation or electricity. In this protocol, an N95 FFR is placed in a sealed glass container which is placed in a container of water that has been boiled previously and taken off heat before treatment of a mask. The average filtration efficiency measured after 5 treatment cycles of this method remained above 97% for particles sized 0.3-4.99 μm at a flow rate of 2.83 l/min, indicating filtration efficiency was not affected by this decontamination method. This outcome is consistent with previously reported literature, where many N95 FFR models have been shown to survive treatments of similar heat and humidity conditions without loss of filtration efficiency. Increasing the boiled water volume while maintaining vessel size allows for a longer treatment duration at high temperatures. A separate protocol in which respirators were held in Ziploc bags resulted in filtration efficiencies being reduced to below 95% after some treatment cycles.
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