Comparison of Face Masks by Arduino Sensors

By Berk Balkir, Veronique Lankar, and Yelda Hangun
Department of Biochemistry and Economics, College of Arts and Sciences

Abstract

The COVID-19 pandemic in early 2020 has created a health crisis around the world. There have been many precautions taken against the virus, such as social distancing and the use of personal protective equipment. Face masks are an essential part of personal protective equipment, especially for essential workers. Although the pandemic has caused a high demand for facemasks, there is limited scientific knowledge available on the various types of masks. Knowledge about the air quality inside the different facemasks could be beneficial for both the COVID-19 pandemic and future disease outbreaks, which will seemingly increase in the future. There are different types of masks, ranging from tight-fitting N95 respirator masks to looser surgical masks to homemade cloth masks. Herein, N95 respirator masks, surgical masks, cloth face masks, and surgical masks on top of N95 respirator masks were compared in terms of CO_2 levels, Volatile Organic Compound levels (VOCs), temperature, humidity, and O_2 concentrations. To record these measurements, Arduino-based sensors were constructed and utilized for the measurements. It was found that the N95 mask and the surgical mask on top of the N95 mask trapped the highest concentration of carbon dioxide, VOCs, temperature, humidity, and the lowest oxygen levels compared to the surgical mask and cloth mask.

Introduction

As a result of the COVID-19 outbreak in early 2020, many individuals have begun to wear many different types of protective face attire. Previously, face masks were mostly used by healthcare workers who cared for patients with respiratory infections or to prevent the spread of infection during surgery. Because of the pandemic, the CDC recommends that "people wear cloth face coverings in public settings and when around people who don't live in your household, especially when other social distancing measures are difficult to maintain." Some examples of protective face wear include N95 respirator masks, surgical masks, and cloth face masks. Healthcare workers and other medical first responders wear surgical masks on top of N95 respirator masks to protect themselves against the coronavirus.

While surgical masks do not seal the area around the mouth and nose, N95 respirator masks protect against viruses and bacteria in addition to sealing the area around the mouth and nose (Smith et al., 2016). Surgical and N95 respirator masks use non-woven fabrics made from plastics such as polypropylene, polycarbonate or polyethylene (Chua et al., 2020). Besides these materials, N95 respirator masks contain several metal parts. The mask uses steel for the staples to secure the straps to the mask and aluminum for the bendable nose clip.

While these aforementioned types of face wear may protect an individual against outside bacteria and disease, essential workers need to wear the face masks for long hours, and this may induce physiological stress on them. It was reported that healthcare workers develop de novo headaches or exacerbation of their pre-existing headache disorders because of prolonged use of N95 respirator masks (Ong et al., 2020; Lim et al., 2006). Wearing an N95 respirator mask triggers different heart rate and discomfort among healthcare providers (Zhu et al., 2014). Usage of an N95 face mask affects the inhaled gas concentrations as a higher concentration of CO_2 becomes trapped in the masks, thus lowering the O_2 levels available for respiration (Tong et al., 2015). Additionally, higher temperatures and humidity in facemasks can alter heart rate and trigger subjective perception of discomfort (Li et al., 2005).

CO_2 is a colorless, odorless, and tasteless gas that makes up 0.04% of the total gas composition in dry air. While the average outdoor CO_2 concentrations are approximately 400 ppm, the typical average indoor concentration can reach up to several thousand ppm (Satish et al., 2012). As humans breathe, each cell takes in oxygen to complete cellular respiration and generates CO_2, which is removed from the body during exhalation. Exhaled breath is usually made up of around 40,000 ppm CO_2 (Wood et al., 2014). As CO_2 is exhaled inside a mask, the amount of O_2 inside the mask decreases. The Occupational Safety and Health Administration, OSHA, determined the optimal range of oxygen in the air, for humans, to be between 19.5% and 23.5% (Spelce et al., 2016). When O_2 concentrations drop from 19.5% to 16%, the cells fail to receive the oxygen necessary to function properly. The increase in amounts of CO_2 and the subsequent decrease in oxygen levels within a face mask can cause an individual's mental abilities to become impaired in addition to symptoms including dizziness, confusion, fatigue, vertigo, headaches, and tinnitus (Ong et al., 2020). The accumulation of CO_2 in the body initiates respiratory acidosis which also causes headache, confusion, anxiety, and drowsiness (Azuma et al., 2018).

Besides CO_2, Volatile Organic Compounds (VOCs) are also present in human breath. Humans emit different VOCs, such as hydrocarbons, alcohols, ketones, and aldehydes. In most healthy individuals, the most prominent VOCs emitted are isoprene, acetone, ethanol, and other alcohols (Fenske et al., 1999). VOCs accumulate in the face masks and may cause headache, dizziness, and confusion. An increase in temperature and humidity inside the different types of face masks can lead to difficulty in breathing. Shortage of oxygen stimulates the sympathetic nervous system and increases heart rate which results in fatigue, headache, and reduced mental performance in individuals (Li et al., 2005).

There is a great interest in open-source microcontroller development boards such as Arduino for sensing, data acquisition, and educational purposes (Grinias et al., 2016). Arduino is a company that builds low-cost, low-power prototyping boards and supports them through a website. The sensors are easily connected to the platform turned to air quality acquisition systems since it is used as an interface between the sensors and the SD card where data is logged in or between the sensors and a serial monitor. Since the development board uses an open-source operating system, it is easily customized and optimized for the constructed sensor (Arduino, n.d). Arduino-based sensors are small, low-cost and provide highly accurate, reliable results in various settings.

Nowadays, students in science departments are encouraged to use development boards like open-source Arduino platforms to collect data with sensors. These Arduino-based sensors are very portable, expandable, and customizable for various areas of study. This can be done without specialized software or hardware skills. Additionally, code can be developed through the Arduino-friendly Integrated Development Environment. Thus, Arduino sensors can be utilized to measure various parameters of novel face masks or other new devices that may be implemented by doctors or civilians to protect individuals during future pandemics.

The aim of this research article is to compare the different types of face masks, namely the N95 respirator mask, surgical mask, cloth face mask, and surgical mask on top of the N95 respirator mask in terms of CO_2 levels, VOC concentrations, temperature, humidity, and O_2 concentrations. Arduino microcontroller sensors were assembled and utilized for the measurements inside the different types of masks. N95 masks would have higher levels of carbon dioxide, VOCs, humidity, temperature, but lower oxygen levels than surgical and cloth masks.

Materials and Methods

The experiment was conducted with a subject placing the sensors into their respective masks and then moving around periodically. The data obtained was sent to a computer program that automatically generated graphs.

The experiment was conducted at 26°C (controlled by a thermostat) and was conducted in the same workspace. The subject had correct placement of the mask at all times (never lowered the mask and never had the mask below the nose). The lightweight sensors were secured inside the mask using tape to ensure no infiltration of outside air. The individual conducting the trials was the same throughout the experiment. The subject was a non-smoker who had no cardiovascular issues. All of the experiments were conducted three times and averaged to ensure accurate results and to minimize error.

Due to their ease in programming and connectivity, SGP30 VOC & CO_2, SHT31-D temperature & humidity modules from Adafruit and O_2 sensor from Grove Company were built and utilized. The VOC & CO_2 module was attached to the Arduino and temperature & humidity sensor have been added to the acquisition system. Throughout the experiments, the sensors were powered from a computer via a USB port. The SD-card module was also added as a backup. The program was written in a free and open Arduino software source. The program enabled the sensors' proper use. The data collected was sent to a computer, via a USB port, every minute and was later transferred to Microsoft Excel.

The SGP30 Multi-Pixel Gas sensor could detect a wide range of VOC and CO_2 concentrations. The sensor had a small microcontroller that read the analog voltage, tracked the baseline calibration, and calculated VOC and CO_2 concentrations. The sensor measured CO_2 concentrations within a range of 400 to 60,000 parts per million (ppm), and VOC concentrations within a range of 0 to 60,000 parts per billion (ppb) (Adafruit, n.d).

Along with the SGP30 VOC & CO_2 sensor, the SHT31-D temperature and humidity sensor was utilized because it provided high accuracy and calibration. The sensor collected the data and converted analog temperature (in °C) and humidity (in % relative humidity) signals to digital signals. The sensor had an excellent ±2% relative humidity and ±0.3°C accuracy. Figure 1 shows a photograph of the SGP30 VOC & CO_2 and humidity & temperature sensors sharing an Arduino-based acquisition system.

A Grove-Gas O_2 Sensor was utilized to measure the oxygen concentration in the facemasks. The sensor generated currents that were proportional to the O_2 concentration in the air (Seeed Studio Wiki, n.d). While it has a humidity range of 0-99%, it also had a temperature range of 20°C to 50°C, which made the sensor suitable for this project. To calibrate the sensor, a free code provided by the Grove-Gas company was implemented. Figure 2 shows the O_2 sensor connected to the Arduino board.

The details of codes, schematics for circuits, and examples of the display can be found in supplementary materials (Lankar, 2021). Graphs of the data were created using Microsoft Excel spreadsheets.

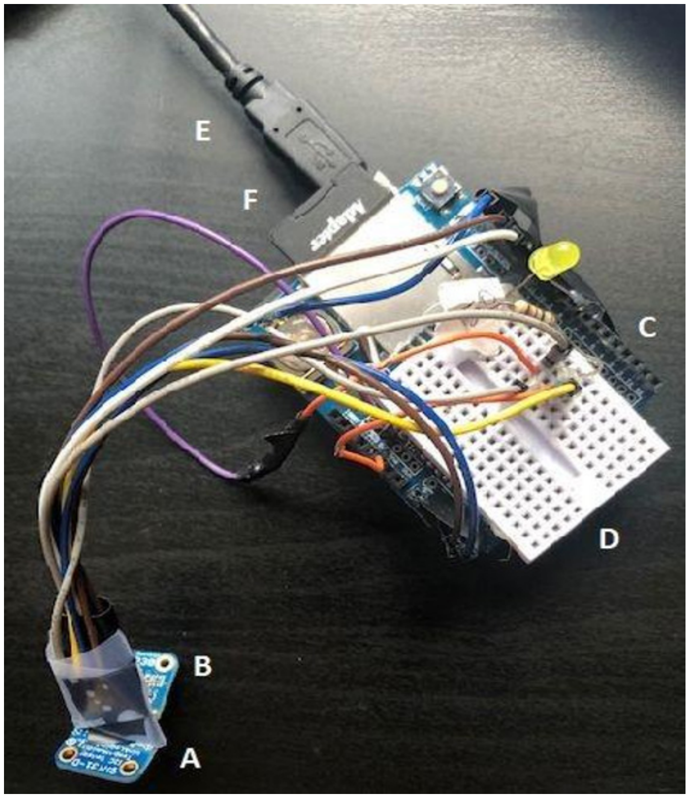

Figure 1: Photo of the VOC & CO_2 and humidity & temperature sensors sharing a development board.
There are six parts in the system: (A) VOC & CO_2 sensor, (B) Humidity & Temperature sensor, (C) Development Board, (D) Data logger shield with SD card and breadboard with signaling LED circuit, (E) USB Port Connection (F) Connection

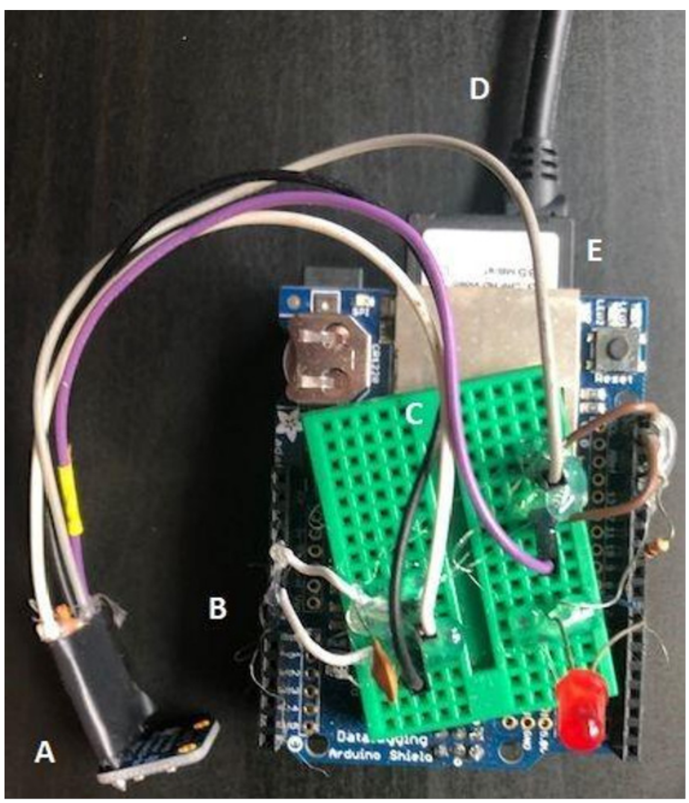

Figure 2: Photo of the Grove-Gas O_2 sensor connected to the Arduino board.
There are five parts in the system: (A) O_2 sensor, (B) Arduino Board, (C) Development Board, (D) Data logger shield with SD card and breadboard with signaling LED circuit, (E) USB Port Connection.

Results and Discussion

Five sensors, measuring VOC, CO_2, O_2, humidity, and temperature levels, were placed inside the four different types of masks to determine the air quality within the masks relative to the air quality outside the mask in the same location. In order to compare the conditions inside the mask with the conditions inside the room, a certain amount of time was allotted for the sensors to take measurements of the room's condition before and after each trial. This can be observed for all the graphs as the flat sections found at the beginning and end display when the masks were not put on and the sensors were measuring the room's CO_2, O_2, humidity, temperature, and VOC concentrations. An example of this can be seen in the Figure 7 for the time intervals ranging from 0-13 minutes and 105-118 minutes. For each parameter in the experiment, since the sensors used in the experiment have a margin of error, the zoxygen concentrations in the N95 mask and the surgical mask on top of the N95 mask's oxygen concentration were not compared to one another. The same was done for the comparison between the cloth and surgical mask.

Figure 3 shows the oxygen concentration (%) over time. The oxygen concentration decreased after all of the different masks were put on. However, on average, the cloth mask had the highest oxygen concentration while the N95 mask with surgical mask had the lowest oxygen concentrations. For the cloth mask, the percent difference between the O_2 concentration inside the mask and outside the mask was around 2.5%. For the N95 with surgical mask, the percent difference between the O_2 concentration inside the mask and outside the mask was around 4%. In all the graphs, there are peaks and troughs that are created by a change in the mask wearer's activity. These peaks and troughs occur at around the same time for each of the four masks for each parameter.

As seen from Figure 4, the highest CO_2 concentrations observed within the masks were observed with the surgical mask on top of the N95 mask, while the lowest accumulated CO_2 concentrations were measured with the cloth mask. For the surgical mask on top of the N95 mask, the percent difference between the CO_2 concentration inside the mask and outside the mask was around 3500%. For the cloth mask, the percent difference between the CO_2 concentration inside the mask and outside the mask was around 1000%.

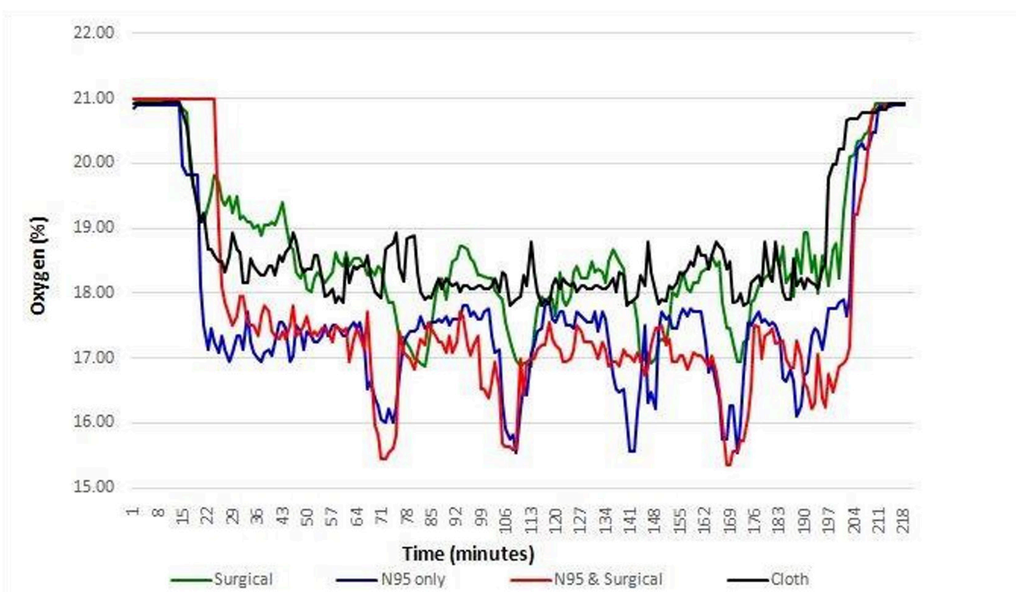

Figure 3: Oxygen (O_2) concentration (%) for different types of masks over time. *The data shown for each mask are the average of the results of 3 different trials. During the experiment, the subject periodically performed physical activity, which led to the O_2 dips at times 71, 106, 141, and 169 minutes.*

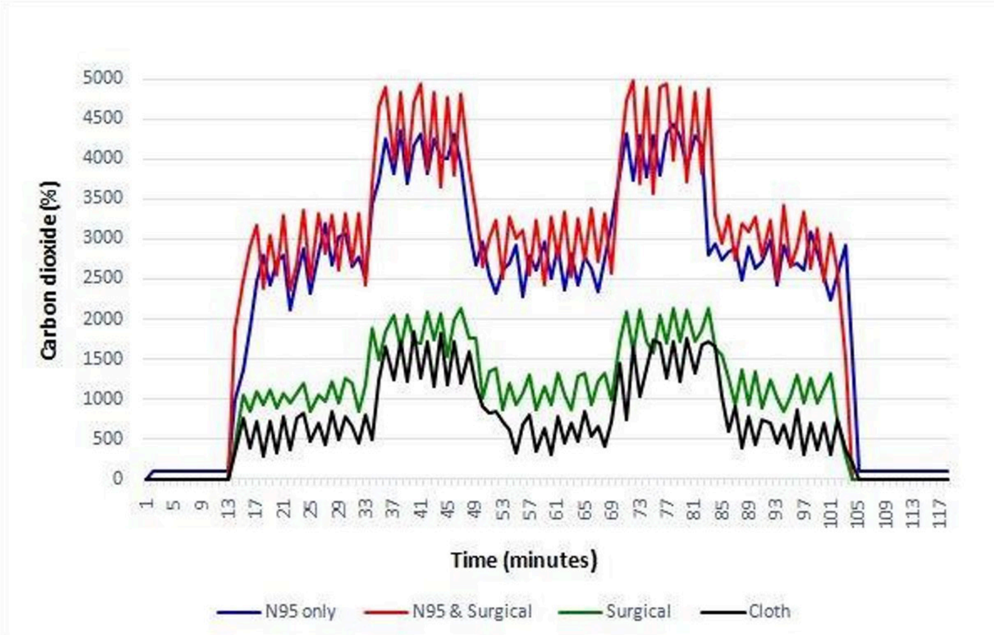

Figure 4: Carbon dioxide (CO_2) concentration (%) for different types of masks over time. *The data shown for each mask are the average of the results of 3 different trials. During the experiment, the subject periodically performed physical activity, which led to the CO_2 increases at times 37-49 and 73-85 minutes.*

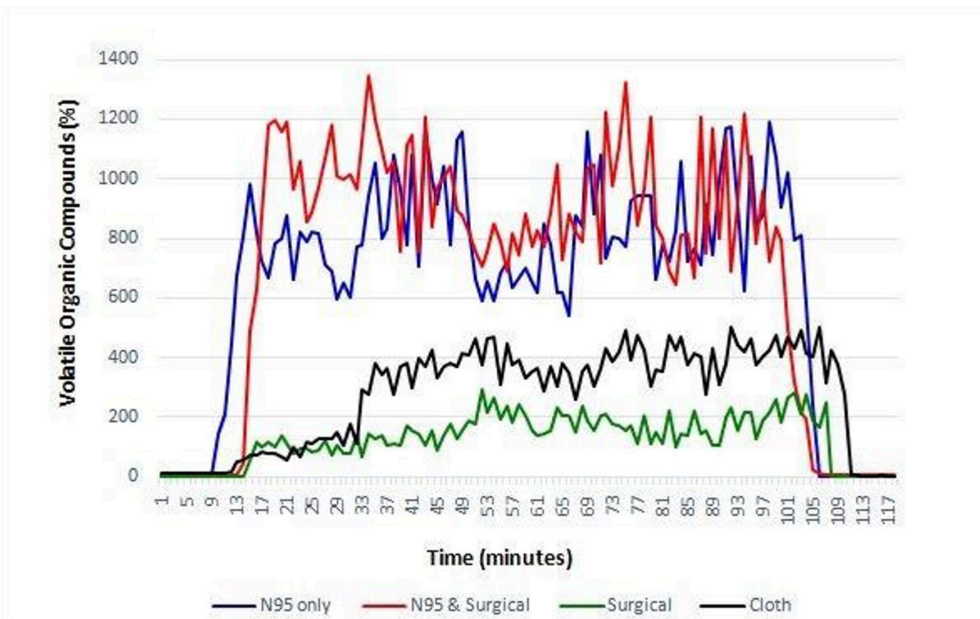

Figure 5: Volatile Organic Compounds (VOC) concentration (%) for different types of masks over time. *The data shown for each mask are the average of the results of 3 different trials.*

Figure 5 shows that the VOC concentration was greatest for the surgical mask on top of the N95 mask, while the VOC concentration was lowest for the surgical mask. For the surgical mask on top of the N95 mask, the percent difference between the VOC concentration inside the mask and outside the mask was around 1000%. For the surgical mask, the percent difference between the VOC concentration inside the mask and outside the mask was around 200%.

As seen from Figure 6, the temperature inside the various masks increased the most for the surgical mask on top of the N95 mask. While the temperature inside the surgical mask and the cloth mask also increased, the temperature increase inside these two masks was less drastic. For the surgical mask on top of the N95 mask, the difference between the temperature inside the mask and outside the mask was around 10.5°C. For the cloth mask, the difference between the temperature inside the mask and outside the mask was around 7°C.

Figure 7 indicates that the humidity inside the various masks increased the most for the surgical mask on top of the N95 mask and the N95 mask. While the humidity levels inside the surgical mask and the cloth mask also increased, the increase in the humidity levels inside these two masks was less drastic. For the surgical mask on top of the N95 mask, the percent difference between the humidity concentration inside the mask and outside the mask was around 45%. For the cloth mask, the percent difference between the humidity concentration inside the mask and outside the mask was around 35%.

Figure 8 shows the pictures of the different face masks. While surgical and cloth masks are worn by the public, N95 respirator masks and surgical masks on top of the N95 respirator masks are worn by essential workers including healthcare professionals.

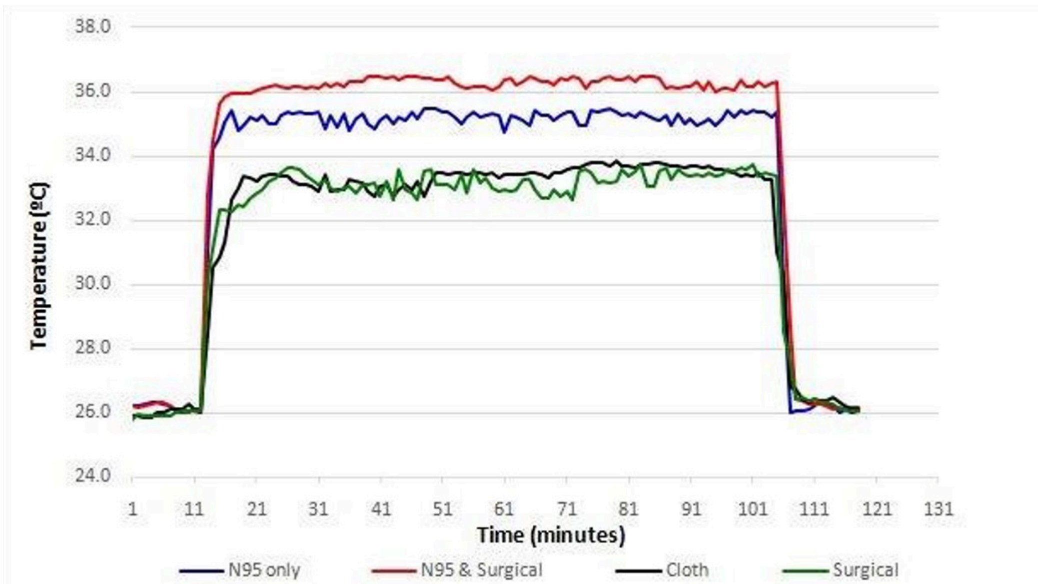

Figure 6: Temperature (°C) for different types of masks over time. *The data shown for each mask are the average of the results of 3 different trials.*

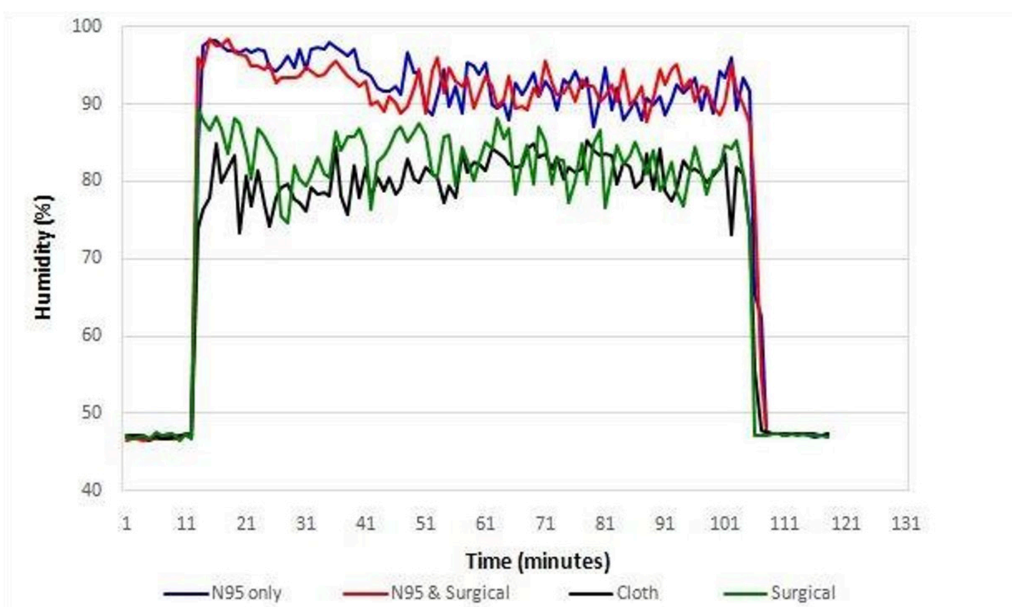

Figure 7: Humidity (%) for different types of masks over time. *The data shown for each mask are the average of the results of 3 different trials.*

Figure 8: Picture of face masks used. *Surgical mask (top left), N95 mask (top right), Cloth mask (bottom left), Surgical mask on top of N95 mask (bottom right).*

Figure 3 shows that the O_2 concentration decreased after all the different masks were put on. However, on average, the surgical mask on top of the N95 mask and the N95 mask alone had the lowest O_2 concentrations because the tighter seal of these masks probably decreased air flow, thus causing O_2 levels to decrease further. In contrast, because the surgical mask and the cloth mask allowed for more air flow, the cloth mask and the surgical mask had the highest O_2 concentration on average. As previously mentioned, OSHA determined the optimal range of oxygen in the air for humans to be between 19.5% and 23.5% (Spelce, 2016). When O_2 concentrations drop from 19.5% to 16%, the cells fail to receive the oxygen necessary to function properly. In Figure 3, the oxygen concentration fell to 15.5% at times for the N95 and the surgical mask on top of the N95 mask. However, for the surgical mask the O_2 concentration at most fell to 16.9%. For the cloth mask, the O_2 concentration at most fell to 17.9%. To mimic real-life situations, measurements were also taken while walking and talking. The dips in all the respective graphs display the moments in which the individual was engaging in these physical activities.

As observed in Figure 4, as the O_2 concentration decreased, the CO_2 concentration increased. This is because CO_2 and O_2 have an inverse relationship as oxygen is breathed in while carbon dioxide is exhaled. Thus, as the CO_2 amount increases, the O_2 amount will decrease. As expected, the highest CO_2 concentrations were observed with the surgical mask on top of the N95 facemask and the N95 facemask alone, while the lowest accumulated CO_2 concentrations were measured with the surgical mask and the cloth mask. The peaks observed in the data display moments in which the individual was engaging in physical activity such as walking and talking.

Figure 5 suggests that the VOC concentration was greatest for the surgical mask on top of the N95 mask and the N95 mask, while the VOC concentration was lowest for the surgical mask and the cloth mask. As aforementioned, since the surgical mask on top of the N95 mask and the N95 mask had the least air flow, the VOCs generated from the individual's breath were unable to escape to the outside of the mask and consequently accumulated over time. The peaks observed in the data display moments in which the individual was engaging in physical activity.

As seen in Figure 6, the temperature inside the various masks increased the most for the surgical mask on top of the N95 mask and the N95 mask. Since these masks offer less air flow than the surgical mask and the cloth mask, the air inside the surgical mask on top of the N95 mask and the N95 mask was unable to be replenished. While the mean human body temperature is 37°C, the mean human breath is between 31.4°C and 34.8°C. As the breath accumulated inside the mask, so did the temperature of the exhale. Thus, the temperature increased greatly until a certain equilibrium was attained. While the temperature inside the surgical mask and the cloth mask increased, it was less drastic than the N95 respirator mask and the surgical mask on top of the N95 respirator mask due to more airflow.

As displayed in Figure 7, the humidity inside the various masks increased the most for the surgical mask on top of the N95 mask and the N95 mask. Since these masks offer less air flow than the surgical mask and the cloth mask, the air inside the surgical mask on top of the N95 mask and the N95 mask was unable to be replenished. As a result, the humidity increased since water vapor is present in human breath. Humidity levels increased because there is water vapor present in human breath. Similar to the VOCs, if there's inadequate air flow, the humidity levels will increase substantially as the water vapor would be unable to escape to the outside of the mask. The humidity levels inside the surgical mask and the cloth mask did not increase as drastically as the humidity levels for the other types of face masks, as they allow for added airflow. If properly fitted, the temperature and humidity inside the face mask reflect those of a human breath.

It was found that the N95 mask and the surgical mask on top of the N95 mask had the highest CO_2, VOC, temperature, humidity, and the lowest O_2 levels compared to the surgical mask and the cloth mask. This information is not only relevant to the COVID-19 pandemic but can also be applied in the case of future pandemics to prevent disease dissemination. As a result of this experiment, it can be extrapolated that face masks that can interfere with an individual's breathing, such as N95 masks and surgical masks on top of N95 masks, may not be favored in intense physical activity. However, due to their strong protection from viruses, the aforementioned masks may be favored in more sedentary situations.

The entire cost of each sensor was around $40, which is significantly more affordable than commercial sensors. While the sensors used in the experiment were portable and easy-to-use, they provided a good level of accuracy and reliability. The project can be an excellent example of interdisciplinary research for undergraduate students. While computer science and/or physics students could build the sensors and write codes, biology, chemistry, and environmental science students could interpret the data and use the sensors for various applications. Additionally, Arduino-based sensors can be used to measure various health aspects of new face masks or other devices that may be implemented to protect individuals during future pandemics.

Acknowledgements

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