https://doi.org/10.36518/2689-0216.1321

Original Research

CO_2 Levels Behind and in Front of Different Protective Mask Types

Hossein Akhondi, MD[1]; Sassan Kaveh, MD[2]; Kimball Kaufman, DO[3]; Tina Danai, RN[2]; Napatkamon Ayutyanont, PhD[4]

Author affiliations are listed at the end of this article.

Correspondence to:
Hossein Akhondi, MD
HCA Florida West Hospital
8383 N Davis Hwy
Pensacola, Fl 32514
(Hossein.akhondiasl@HCAhealthcare.com)

Abstract

Objectives
Many individuals have difficulty adapting to face mask use and report symptoms while using masks. Our primary objective was to determine whether continuous mask-wearing causes elevated levels of carbon dioxide (CO_2) behind the facemasks.

Methods
CO_2 concentrations were measured behind 3 different types of face masks and were compared to CO_2 concentrations at the mask front in 261 subjects who continuously wore masks for at least 5 minutes. These CO_2 concentrations were also measured in several randomly selected subjects after a 5-minute walk.

Results
There were significantly higher CO_2 concentrations behind the mask (3176 ppm) compared to the front (843 ppm) with an average of 49 minutes of continuous mask use. Of all the subjects, 76.6% had a behind-the-mask CO_2 concentration of more than 2000 ppm (the threshold for clinical symptoms), and 12.2% had a CO_2 concentration of at least 5000 ppm (occupational health exposure limit). The CO_2 level behind the N-95 masks was highest (especially after exertion) and was lowest behind cloth masks. The combination of warm ambient temperature, an N-95 mask, exercise, and young age appeared to induce exceedingly high CO_2 levels that should be avoided.

Discussion
Although masks might be necessary for healthcare workers or to lessen the spread of airborne disease, we found that elevated CO_2 concentrations were present while wearing them. Elevated CO_2 concentrations have historically caused symptoms of CO_2 toxicity. Periodic mask breaks in designated areas may be needed to avoid adverse effects.

Conclusion
The use of masks increased the CO_2 concentration in the air behind them to levels historically associated with toxicity.

Keywords
face mask; masks; CO_2 level; CO_2 toxicity; carbon dioxide; respiratory protective devices; personal protective equipment; COVID-19; SARS-CoV-2; coronavirus infections; N95 respirators; N95 mask

Background

There is a growing consensus about the value of face masks for reducing the spread of severe acute respiratory syndrome coronavirus type 2 (SARS-CoV-2), but this has not always been the case. Initially, little was known about the new virus. Mask policies had to be developed based on the best available evidence, following scientific models that drew on data from earlier epidemics involving similar viruses.[1] Consequently, guidance about mask-wearing has varied from country to country, and some major health organizations, including the World Health Organization (WHO), have changed their advice about masks over time.[2]

Observational studies, systematic reviews, and epidemiologic modeling support the public's use of masks, especially surgical masks, to mitigate coronavirus disease 2019 (COVID-19) transmissions and deaths.[3] However, the practice of mask-wearing has also been controversial and politicized, especially in the United States (US).[4]

Many people using a face mask reported feelings of suffocation, tiredness, shortness of breath, dizziness, and fatigue, especially after prolonged use or after using heavy filter masks such as N-95s.[4] These signs could indicate carbon dioxide (CO_2) toxicity (**Table 1**). CO_2 levels in outdoor air typically range from 300 to 400 parts per million (ppm) (0.03% to 0.04%) but can be as high as 600-900 ppm in metropolitan areas. Clinical symptoms of toxicity might occur when CO_2 levels are above 2000 ppm, and 5000 ppm is the CO_2 work exposure limit.[5,6] The most widely recognized exposure limits for CO_2 reference an 8-hour time-weighted average of 5000 ppm, with a 15-minute short-term exposure limit of either 15 000 ppm or 30 000 ppm.[7]

Masks reduce the free flow of air, making it logical to assume that CO_2 concentrations would be elevated behind the masks. It is unknown if prolonged rebreathing of CO_2 during prolonged mask-wearing can cause symptoms. The seriousness of symptoms would depend on the concentrations of CO_2, the length of time a person is exposed, physiologic variations, and existing conditions. Low to moderate exposure to CO_2 is generally reversible once a person is removed from a high CO_2 environment.[8]

To our knowledge, there have only been a few measurements of CO_2 behind masks.[9] Given the flux in recommendations and the uncertainty surrounding the possible community-wide impact of facemask usage, we measured CO_2 levels in subjects wearing various mask types and compared it to the CO_2 levels in front of their masks in an outpatient internal medicine setting, a lecture hall, and at a residency training program all in Las Vegas, NV.

Methods

Our inclusion criteria included subjects 18 years of age or older who had used a facemask for more than 5 minutes before testing. There were no exclusion criteria. The research protocol was reviewed and exempted by the HCA Healthcare Institutional Review Board (IRB) for Graduate Medical Education (GME) [Submission-ID #: 2020-566]. All human participants gave informed consent, and all methods were carried out per relevant guidelines and regulations.

The study was performed at Frontier Medical Group, an outpatient, private internal medicine office. All patients who visited the office during the 12-week enrollment period were asked to participate in the study. We also recruited the internal medicine residents, faculty, and medical students from a residency training program. In addition, participants in the daily didactic lectures of the medicine department in the lecture hall were asked to be subjects for the study. All testing was conducted inside the clinic and lecture halls. All three sites are located in Las Vegas, NV.

After obtaining informed consent, a registered nurse gave the participants a questionnaire. The questionnaire inquired about the participant's age, gender, weight, type of mask (eg, cloth, N-95, surgical, mask with a valve), the minimum duration they wore their mask, past medical history, and social history. Two identical, commercially available, non-invasive sensors (Arizona Instruments Model 7755) measured CO_2 concentration, humidity, and temperature, which were measured about 5 centimeters in front of the participants' masks. Then the instrument's plastic tip, where the sensor is located, was inserted behind the participant's mask in front of their mouth to measure the

Table 1. CO_2 Concentration in Ventilated Air and Related Symptoms

CO_2 concentration in parts per million	Settings and possible clinical symptoms
250-350	Outdoor air
350-1000	Indoor air (with adequate ventilation)
1000-2000	Poor air quality (with possible drowsiness)
2000-5000	Stagnant and stale air (headaches, sleepiness, loss of attention and concentration)
5000-40 000	Workplace exposure limit and above
>40 000	Oxygen deprivation, nausea and vomiting, sympathetic symptoms, anoxic brain injury, coma

same parameters. Subjects were asked to hold their breath during the reading. It takes about 5 seconds for the machine to stabilize for each new reading. The plastic tip was sanitized with alcohol pads before and after each use. The tip was also steamed regularly with a commercial steamer to assure complete sanitation. The airflow in the room was the same during the tests. Both instruments were re-calibrated daily, and all measurements were done inside the rooms (clinic and lecture hall) with no outside measurements. We did not modify the tightness of the mask fit on any subjects.

Light exertion was defined as indoor walking for 5 minutes on a level surface. CO_2 was measured for a random subset of subjects (n=96) who agreed to participate before and after light exertion. The intensity of exertion and walking was not controlled and was paced by the individual subjects.

Chi-square analysis and binary logistic regression evaluated statistically significant differences between groups for each mask modality using SPSS version 26 (www.ibm.com/spss/statistics).

Results

A total of 261 participants (140 females and 121 males) were included in the study. Ages ranged from 18-94 years old (mean ± SD, 56.5 ± 18.9). The mean weight was 182 ± 54.9 lbs. Of the 261 participants, 26 were smokers, 32 had diabetes, 17 had asthma, and 12 had chronic obstructive lung disease.

Participants had a baseline mean CO_2 level of 843 ppm in front of their masks. They wore their masks continuously for a mean duration of 49 ± 77 minutes. The mean CO_2 level behind their masks was 3176 ± 1830 ppm. The mean ambient air temperature testing was 24.1 ± 6.7 degrees Celsius. Overall, the CO_2 in front of the mask was significantly lower than the CO_2 behind it while seated or during exertion (P<.01) (**Table 2**). Behind-mask CO_2 of at least 2000 ppm was measured in 200 subjects (76.6%), and a behind mask CO_2 of at least 5000 ppm was measured in 32 subjects (12.2%) (**Table 2**). All the measurements were done indoors. The room CO_2 was not the same as the front of the mask CO_2 since there was exhaled CO_2 5 cm in front of the mask.

Surgical masks were worn by 159 (61%) of the participants; 80 (30.6%) wore cloth masks; 22 (8.4%) wore N-95 masks (**Table 2**). We did not encounter any valve masks. Mean CO_2 levels were lowest when sampling behind cloth masks (2759 ppm, **Table 2**) and highest behind N-95s (4588 ppm). Compared to a surgical mask, a cloth mask was associated with a lower risk of behind-mask CO_2 levels reaching the 2000 ppm level (odds ratio (OR) = 0.52; 95% CI, 0.265-1.003; P=.051, NS). Compared to the surgical mask, the N-95s were associated with 6.4 times higher risk of behind-mask CO_2 level reaching the 5000 ppm level (95% CI, 2.192-18.492; P<.01). The CO_2 level increased with exertion and was 4975 ppm in the N-95 group (**Table 2**).

An increase in age or number of smoking years decreased the risk of significant CO_2 elevation: the risk of having a behind-mask CO_2 level reaching 2000 ppm level decreased by 2% and 4.4%, respectively, for age and smoking years (P=.03 and .01). Logistic regression revealed that for each year of age increase, the risk of having a behind-mask CO_2 level reaching the 5000 ppm level decreased by 4.4% (P<.01).

Table 2. Different Masks and CO_2 Concentrations Behind Them (ppm), in Front of Them (ppm), and After a 5-Minute Exertion on a Level Surface

	Total number	Front of the mask CO^2 mean (ppm)	SD	Total number	Behind mask CO^2 mean (ppm)	SD	Total number	Exertion mean CO_2 (ppm)	SD	*P*-values
Surgical mask	159	842.5	146.3	159	3191	1610	46	3759	1138	<.001[a,b,c]
N-95 mask	22	1029	1240	22	4588	2627	8	4975	2163	<.001[a,b]
Cloth mask	80	792.9	121.3	80	2759	1345	42	3714	1739	<.001[a,b,c]
All masks	261	843	381.1	261	3176	1704	96	3841	1543	<.001[a,b,c]

Post-hoc pair-wise comparison *P*<.05:

[a] Front of the mask vs. behind mask

[b] Front of the mask vs. exertion

[c] Behind the mask vs. exertion

Although not attaining the level of statistical significance, with each pound increase in weight, the risk of having a behind-mask CO_2 level reaching 5000 ppm level increased by 0.6% (*P*=.08).

Finally, for each degree Celsius increase in room temperature during light exertion, the risk of having a behind-mask CO_2 level reaching 2000 ppm increased by 1.5 times (*P*=.05).

Discussion

Facemasks are essential components of personal protective equipment for healthcare workers in hospitals and civilians alike. Notably, masks help prevent illness in healthy persons and prevent asymptomatic transmission, especially during a global pandemic.[9] Although indoor mask use was mandatory in many US states due to COVID-19, masks had been in regular use in hospitals and operating rooms before the COVID pandemic.[10]

As evidenced by the findings in our study, the CO_2 concentrations were elevated behind cloth masks, surgical masks, and N-95 masks. Even modestly-elevated CO_2 levels can cause physiological changes, dizziness, shortness of breath, headache, and other symptoms. Heavy-filter facemasks (N-95) caused higher CO_2 concentrations behind the mask and could be associated with a higher frequency of associated symptoms.[11]

It is possible that some of the behaviors observed during the pandemic were attributed to mask use and CO_2 toxicity. Agitation, anger, depression, and confusion can be related to mask use. Increased disruptive behavior by airline passengers was widely publicized during the pandemic.[12] Our data did not determine whether federal airline mask mandates are linked to such behaviors. Still, our measurements suggest that prolonged mask-wearing, especially with N-95 masks, can elevate CO_2 levels significantly.

In a study of 158 healthcare workers using primarily N-95 masks, it was noted that 81% developed new headaches within 10 to 50 minutes of starting a shift.[13] After 4 hours, the likelihood of headache was 4 times higher [OR=3.91, 95% CI, 1.35-11.31; *P*=.012].[13] A surgeon in the operating room wears a mask for several hours without a break. Elevated CO_2 levels could explain some of the agitations that can arise when performing a procedure.[14] In a study of 53 surgeons where facemasks were used during a major operation, the oxygen saturation dropped by 1% after 60 minutes, and the pulse rate increased.[15]

In our study, the mean CO_2 concentration increased from 843 ppm to 3176 ppm with continuous mask use of only 49 minutes. After 8 hours of healthcare shift work with no chance to remove the mask, the numbers are presumably even higher. Our study did not screen for symptoms and clinical signs. Future research can focus on those signs.

The behind-the-mask CO_2 concentrations in 76.6% of people in our study were theoretically high enough to cause clinical symptoms, and 12.2% was higher than the limit set forth by occupational health organizations. However, it should be mentioned that a 5000 ppm level in a confined work environment might not necessarily translate to a 5000 ppm level behind a mask. Each breath does bring some fresh air, thereby creating a lower inspired CO_2 ppm behind the mask.

Those wearing cloth masks had the lowest level of CO_2 concentration, followed by those wearing surgical masks and the N-95 group, but all groups had elevated CO_2 levels behind their masks. A rise in temperature, but not humidity, increased CO_2 levels, and therefore it is a factor to be considered in hot regions. The combination of a higher temperature, an N-95 mask, exercising, and young age appeared to be related to elevated CO_2 levels that should be avoided. Notwithstanding other factors, N-95 use and exercise seem non-compatible.

A net CO_2 accumulation will likely cause acidosis. Increased age decreases metabolism, reduces CO_2 production relative to O_2 intake, and reduces the chance of CO_2 toxicity. This reduction might be because older people produce less CO_2 in general, and lung function is diminished by some 40% later in life regardless of the respiratory muscle functions.[16] Therefore, older people might not be as at-risk as younger individuals. The same is true about smoking history. The longer someone has smoked, the less CO_2 is emitted from the presumably damaged lungs, and the chances of toxicity decrease. These physiologic effects have been the subject of previous discussions.[16]

How can we confront and handle the potential problems caused by prolonged mask-wearing? There is no easy solution. Perhaps there is a need for a mask break for a few minutes every hour in an isolated area to counter the CO_2 elevation and reset the baseline CO_2 without increasing the risk of illness transmission. Those with occupations and activities that require exertion or healthcare workers working in high-risk areas that require prolonged use of N-95 masks may be at higher risk for developing symptoms and may need more frequent breaks.

We follow and recommend current guidelines for mask use but also caution against side effects. During the Delta and Omicron surges, mask use likely reduced the number of illnesses and hospitalizations. However, continuous mask use for an average of 49 minutes can elevate CO_2 levels, which are linked to symptoms. As we face the continued threat of airborne and droplet respiratory diseases, one must weigh the benefit of using masks to prevent transmission against possible consequences associated with their usage. All mask types are equally helpful in preventing droplet infections such as influenza, though some are insufficient for protection against airborne pathogens.[17,18] WHO guidelines recommend surgical masks for all patient care, except for N-95 mask use for aerosol-generating procedures. Alternative protective methods such as surgical masks with lesser airway resistance than N-95 could be considered the better choice in the appropriate settings.[18]

Our study has limitations, including the relatively low number of subjects and the fact that CO_2 in front of the mouth and behind the mask does not necessarily correlate to blood CO_2. Arterial blood gas measurements would be the gold standard for that determination, though it is an invasive procedure. When we tested the behind-mask CO_2 level, we had to break the mask's seal for that measurement, which might have affected and decreased the CO_2 concentration. A perfect study might evaluate healthcare workers' blood gas after 8 hours of continuous shift work without removing their masks.

We measured the CO_2 in front of and behind the mask. One might argue that room air versus behind-mask CO_2 levels should have been compared. However, expired gases coming through the mask will likely increase the CO_2 level in front of the mask compared to room CO_2. Therefore, the front-of-the-mask measurement probably reflects the gas concentration that is most likely to be rebreathed.

One opposing argument would be that tight-fitting cloth or surgical masks hold a small air volume relative to the wearer's tidal volume (0.5 L/breath). When the wearer inspires, the room air with closer to 400 ppm CO_2 dilutes the CO_2 inside the mask and reduces the potential for clinical symptoms and toxicity. Despite the high levels of CO_2 inside the mask, the volume of gas in the mask is low, and the wearer's CO_2 is likely not dangerously high. The N-95 and other cone-shaped masks could hold a larger volume of gas which, combined with the higher in-mask CO_2, would be expected to place the wearer at a higher risk for elevated levels.

Some research on exercise performance and mask use has been recently published and has opposing findings. In one study, there was no difference in exercise performance (time to exhaustion) in a small number of subjects wearing cloth masks, surgical masks, or no masks. Nor were there any differences in oxygen (O_2) saturation or tissue O_2 index.[19] The same authors performed a systematic review and concluded that mask-wearing does not affect exercise performance and has minimal impact on physiological variables during exercise.[20] Another article concluded that wearing a mask did not have any physiological consequences, but there might be psychological consequences.[21] Finally, an article published in 2020 promoting a health hypothesis summarized facemasks' adverse physiological, psychological, and health effects. That article has since been retracted.[22]

We hope everyone, particularly healthcare providers, looks at the evidence and science and does not judge the results based on personal preferences, societal inclinations, or partisan thinking. This subject is scientific, and the data should guide people's conclusions. More studies are needed to examine the potential adverse effects of elevated behind-the-mask CO_2, and this pilot could prove helpful as a starting point in this field. More detailed questioning about signs and symptoms of CO_2 toxicity while using masks should also be completed.

Conclusion

While we recommend widespread mask usage during a respiratory disease pandemic, a CO_2 level increase might complicate its use. People using masks have variable degrees of CO_2 elevation, which appear to be influenced by age, ambient temperature, and exertion. A potential remedy is to designate an area to remove masks temporarily to mitigate physiological effects associated with their use. A system to report symptoms related to mask use may also be beneficial.

Contribution Statement

HA developed the concept, edited the protocol, implemented it in clinic and noon meetings, wrote the manuscript, edited it, and submitted it to the journal.
SK had the original idea and secured equipment and staffing.
KK wrote the protocol, presented the protocol to the IRB, and wrote parts of the manuscript.
TD consented the test population, performed the tests, and gathered the data.
NA performed the statistical analyses and edited the manuscript.

Conflicts of Interest

This research was funded in part by a grant from Gamma Medical Research, Inc. (the CO[2] measuring devices manufacturers, commercial steamers, and medical staffing).

Dr Akhondi is an employee of HCA Florida West Hospital, a hospital affiliated with the journal's publisher.

Dr Kaufmann is an employee of MountainView Hospital, a hospital affiliated with the journal's publisher.

Dr Ayutyanont is an employee of HCA Healthcare Graduate Medical Education, an organization affiliated with the journal's publisher.

This research was supported (in whole or in part) by HCA Healthcare and/or an HCA Healthcare affiliated entity. The views expressed in this publication represent those of the author(s) and do not necessarily represent the official views of HCA Healthcare or any of its affiliated entities.

Author Affiliations

1. HCA Florida West Hospital, Pensacola FL
2. Frontier Medical Group, Las Vegas, NV
3. MountainView Hospital, Las Vegas, NV
4. HCA Healthcare Graduate Medical Education, Far West Division, Las Vegas, NV

References

1. Wang J, Pan L, Tang S, Ji JS, Shi X. Mask use during COVID-19: a risk adjusted strategy. *Environ Pollut*. 2020;266(Pt 1):115099. doi:10.1016/j.envpol.2020.115099
2. Cowling BJ, Zhou Y, Ip DK, Leung GM, Aiello AE. Face masks to prevent transmission of influenza virus: a systematic review. *Epidemiol Infect*. 2010;138(4):449-456. doi:10.1017/S0950268809991658
3. Chu DK, Akl EA, Duda S, et al. Physical distancing, face masks, and eye protection to prevent person-to-person transmission of SARS-CoV-2 and COVID-19: a systematic review and meta-analysis. *Lancet*. 2020;395(10242):1973-1987. doi:10.1016/S0140-6736(20)31142-9
4. Esposito S, Principi N, Leung CC, Migliori GB. Universal use of face masks for success against COVID-19: evidence and implications for prevention policies. *Eur Respir J*. 2020;55(6):2001260. doi:10.1183/13993003.01260-2020 3
5. Guais A, Brand G, Jacquot L, et al. Toxicity of carbon dioxide: a review. *Chem Res Toxicol*. 2011;24(12):2061-2070. doi:10.1021/tx200220r
6. Langford NJ. Carbon dioxide poisoning. *Toxicol Rev*. 2005;24(4):229-235. doi:10.2165/00139709-200524040-00003
7. Carbon dioxide health hazard information sheet. United States Department of Agriculture Food Safety and Inspection Service. https://www.fsis.usda.gov/wps/wcm/connect/bf97edac-77be-4442-aea4-9d2615f376e0/Carbon-Dioxide.pdf?MOD=AJPERES
8. Tirupathi R, Bharathidasan K, Palabindala V, Salim SA, Al-Tawfiq JA. Comprehensive review of mask utility and challenges during the COVID-19 pandemic. *Infez Med*. 2020;28(suppl 1):57-63.
9. Roberge RJ, Coca A, Williams WJ, Powell JB, Palmiero AJ. Physiological impact of the N95 filtering facepiece respirator on healthcare workers. *Respir Care*. 2010;55(5):569-577.
10. Li T, Liu Y, Li M, Qian X, Dai SY. Mask or no mask for COVID-19: a public health and market study. *PLoS One*. 2020;15(8):e0237691. doi:10.1371/journal.pone.0237691
11. Permentier K, Vercammen S, Soetaert S, Schellemans C. Carbon dioxide poisoning: a literature review of an often forgotten cause of intoxication in the emergency department. *Int J Emerg Med*. 2017;10(1):14. doi:10.1186/s12245-017-0142-y
12. Helaine O. Air-rage incidents are rising-for lots of reasons. *Washington Post*. July 15, 2021.
13. Ong JJY, Bharatendu C, Goh Y, et al. Headaches associated with personal protective equipment - a cross-sectional study among frontline healthcare workers during COVID-19. *Headache*. 2020;60(5):864-877. doi:10.1111/head.13811
14. Zbar RI. Closing the generational gap in surgery: why so angry?. *Plast Reconstr Surg Glob Open*. 2016;4(10):e1087. doi:10.1097/GOX.0000000000001087
15. Beder A, Büyükkoçak U, Sabuncuoğlu H, Keskil ZA, Keskil S. Preliminary report on surgical mask induced deoxygenation during major surgery. *Neurocirugia (Astur)*. 2008;19(2):121-126. doi:10.1016/s1130-1473(08)70235-5
16. Roman MA, Rossiter HB, Casaburi R. Exercise, ageing and the lung. *Eur Respir J*. 2016;48(5):1471-1486. doi:10.1183/13993003.00347-2016
17. Chu DK, Akl EA, Duda S, et al. Physical distancing, face masks, and eye protection to prevent person-to-person transmission of SARS-CoV-2 and COVID-19: a systematic review and meta-analysis. *Lancet*. 2020;395(10242):1973-1987. doi:10.1016/S0140-6736(20)31142-9
18. MacIntyre CR, Cauchemez S, Dwyer DE, et al. Face mask use and control of respiratory virus transmission in households. *Emerg Infect Dis*. 2009;15(2):233-241. doi:10.3201/eid1502.081167
19. Shaw K, Butcher S, Ko J, Zello GA, Chilibeck PD. Wearing of cloth or disposable surgical face masks has no effect on vigorous exercise performance in healthy individuals. *Int J Environ Res Public Health*. 2020;17(21):8110. doi:10.3390/ijerph17218110
20. Shaw KA, Zello GA, Butcher SJ, Ko JB, Bertrand L, Chilibeck PD. The impact of face masks on performance and physiological outcomes during exercise: a systematic review and meta-analysis. *Appl Physiol Nutr Metab*. 2021;46(7):693-703. doi:10.1139/apnm-2021-0143
21. Scheid J, Lupien S, Ford G, et al. Commentary: Physiological and psychological impact of face mask usage during the COVID-19 pandemic. *Int J Environ Res Public Health*. 2020;17(18):6655. doi:10.3390/ijerph17186655
22. Vainshelboim B. Retracted: Facemasks in the COVID-19 era: a health hypothesis [retracted in: *Med Hypotheses*. 2021;110601]. *Med Hypotheses*. 2021;146:110411. doi:10.1016/j.mehy.2020.110411