How Much CO_2 Builds Up in an N95 Mask - And Does it Matter?

By Kyle Benzle

Abstract

Hypothesis: Wearing an N95 mask will significantly increases intra-mask carbon dioxide (CO_2) levels. I hypothesize that CO_2 concentrations inside the mask will exceed OSHA's permissible exposure limit (PEL) of 5000 ppm for most of the respiratory cycle and that double masking may further increase retention.

Materials and Methods: A Sensirion SCD-30 NDIR CO_2 sensor was placed inside single and double N95 masks (3M 8210) to measure CO_2, temperature and relative humidity at baseline (ambient air), end of inspiration, and end of expiration. A total of 413 measurements were collected. ANOVA and t-tests assessed statistical significance.

Results: CO_2 and humidity levels inside the mask were significantly higher than baseline measurements but there was no statistically significant difference between the 1 and 2 mask configurations.

- **Baseline CO_2:** 518.47 ± 132.7 ppm
- **End-of-inspiration CO_2:** 4567.72 ± 1681.4
- **End-of-expiration CO_2:** 9006.54 ± 1605.0
- **Statistical Significance**: $p < 0.001$
- **Single vs. Double Mask:** No significant difference in intra-mask CO_2 levels.

Discussion: CO_2 inside N95 masks remained above OSHA's 5000 ppm limit for nearly the entire breath cycle only briefly dipping below this threshold at the very end of deep inhalation. End-expiration CO_2 was 9006 ppm, and even during inhalation, CO_2 levels remain significantly elevated, exposing wearers to air consistently above occupational safety limits. Relative humidity, at 90%+ is also above the OSHA referenced guidelines that recommends 30%–60%. No significant difference was observed between single and double masks but a strong CO_2-humidity correlation ($r = 0.87$) suggests moisture retention may contribute to discomfort. This study demonstrates that N95 masks do not clear exhaled CO_2 fast enough to provide consistently safe air quality.

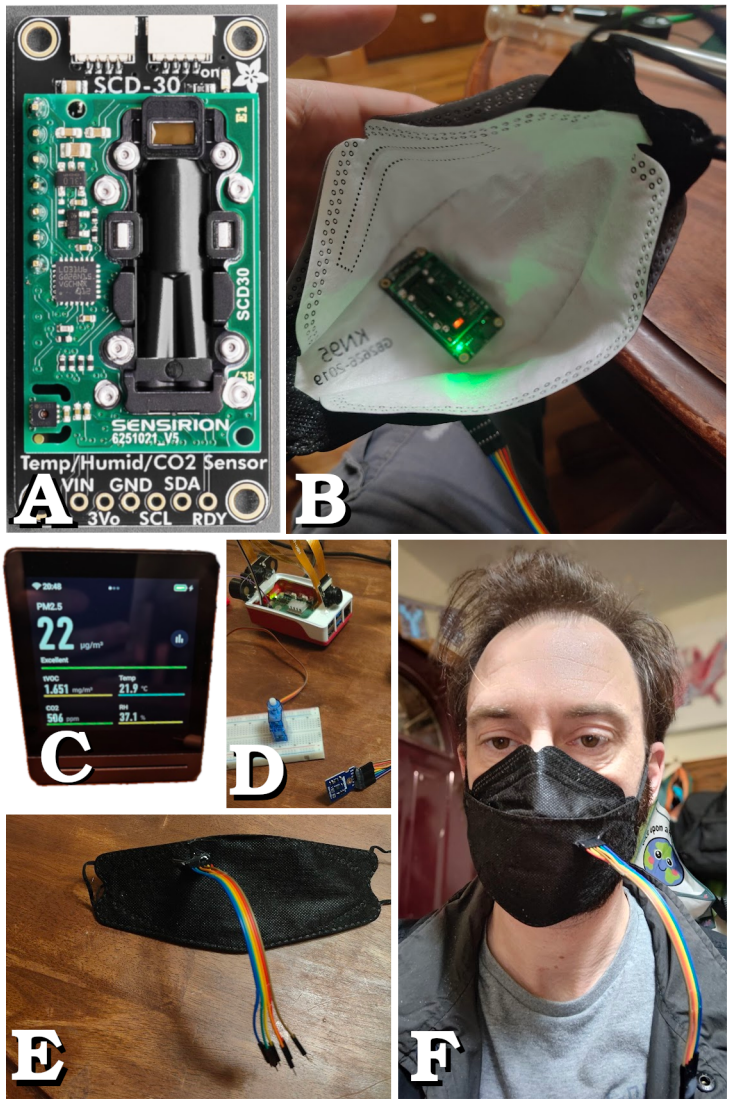

Figure 1: *Experimental Setup and Sensor Configuration. (A) Sensirion SCD-30 NDIR CO_2 sensor used for intra-mask CO_2, temperature, and humidity measurements. (B) Sensor placement inside a 3M 8210 N95 mask. (C) External Qingping AQ Monitor CO_2 monitor used to validate baseline ambient CO_2 levels. (D) Raspberry Pi-based data acquisition system with a custom breadboard interface. (E) Modified N95 mask with external wiring.(F) Subject wearing the instrumented N95 mask for CO_2 measurements during respiration.*

Introduction

N95 respirators are widely used for respiratory protection in healthcare, industrial, and public health settings due to their high filtration efficiency. However, concerns have been raised about the potential accumulation of carbon dioxide (CO_2) inside the mask due to restricted airflow and rebreathing of exhaled air. While N95 masks effectively prevent the inhalation of airborne particles, the buildup of exhaled CO_2 within the mask cavity may impact wearer comfort and respiratory gas exchange.

Several studies have assessed CO_2 accumulation inside masks, often reporting levels between 2000 and 4000 ppm during inhalation [1,2]. However, these studies primarily measure CO_2 levels at the end of inhalation, when CO_2 is at its lowest. In contrast, exhaled CO_2 concentrations regularly exceed 35,000 ppm, and without adequate clearance, significant retention may occur within the mask, exposing wearers to elevated CO_2 levels throughout the breathing cycle. OSHA's permissible exposure limit (PEL) for CO_2 is 5000 ppm over an 8-hour work period [3], yet many prior studies have not directly assessed whether intra-mask CO_2 remains above this threshold for most of the respiratory cycle.

In this study, I measured intra-mask CO_2 concentrations throughout the full breath cycle using a high-accuracy NDIR CO_2 sensor (Sensirion SCD-30) placed inside both single and double N95 masks (3M 8210). Unlike previous studies that report CO_2 at the lowest inhaled concentration, I assessed CO_2 levels at baseline (ambient air), end of inspiration, and end of expiration. Additionally, I recorded temperature and humidity, factors that may influence user discomfort. I hypothesize that intra-mask CO_2 will exceed 5000 ppm for the majority of the respiratory cycle and that double masking may further increase retention. Our findings provide empirical data on CO_2 buildup inside N95 masks, offering insight into the physiological effects of prolonged mask use in occupational and public health settings.

Materials and Methods

Experimental Setup

A Sensirion SCD-30 non-dispersive infrared (NDIR) CO_2 sensor (Figure 1A) was used to measure intra-mask CO_2 concentration, temperature, and relative humidity inside single and double N95 masks (3M 8210, 3M, USA). The sensor was placed inside the mask, near the nostrils, to capture gas composition throughout the respiratory cycle (Figure 1B). The SCD-30 sensor has a measurement range of 400–10,000 ppm CO_2 with an accuracy of ±(30 ppm + 3%), and includes an integrated temperature (±0.3°C) and humidity (±3% RH) sensor.

To validate baseline ambient CO_2 levels, an Qingping AQ Monitor CO_2 monitor (Figure 1C) was used, ensuring that external air measurements were accurate before mask testing. Data acquisition was controlled via a Raspberry Pi 4 Model B (Raspberry Pi Foundation, UK) connected to the sensor through a custom-built breadboard interface (Figure 1D). A modified N95 mask with external wiring (Figure 1E) enabled real-time connectivity and logging of intra-mask gas levels. The study was conducted in a home environment with HEPA filtration and an open window to maintain ambient air circulation.

Measurement Protocol

CO_2 concentration was recorded at three respiratory phases:

1. Baseline (ambient air before mask placement).
2. End of Inspiration (completion of inhalation).

3. End of Expiration (peak exhalation).

The subject wore the instrumented mask (Figure 1F) while following a controlled breathing protocol. A total of 413 measurements were collected (12 baseline, 197 end-of-inspiration, 204 end-of-expiration).

Data Processing and Analysis

All CO_2, temperature, and humidity data were logged via Python scripts on the Raspberry Pi included in supplementary data via GitHub (https://GitHub.com/KyleBenzle/CO2). Statistical analysis included one-way ANOVA for CO_2 differences across respiratory phases, paired t-tests for mask comparisons, and Pearson correlation analysis to evaluate relationships between CO_2, humidity, and temperature. Statistical significance was set at $p < 0.05$.

Data visualizations, including CO_2 trends across respiratory phases, single vs. double mask comparisons, and correlation matrices, were generated. Raw data, sensor specifications, and additional experimental images are provided in supplementary materials

Results

CO_2 Accumulation Across Respiratory Phases

CO_2 levels inside N95 masks were significantly elevated compared to ambient air, with peak levels occurring at end-exhalation. While CO_2 concentration decreased during inhalation, it remained above OSHA's permissible exposure limit (5000 ppm) for most of the respiratory cycle, only briefly dipping below this threshold at the very end of deep inhalation.

Measurement Phase	CO_2 Concentration (ppm) ± SD	Sample Size (n)	Statistical Significance (p-value)
Baseline (Ambient Air)	518.47 ± 132.76	12	-
End of Inspiration	4567.72 ± 1681.43	197	$p < 0.001$
End of Expiration	9006.54 ± 1605.02	204	$p < 0.001$

Table 1: *CO_2 Concentrations by Respiratory Phase*

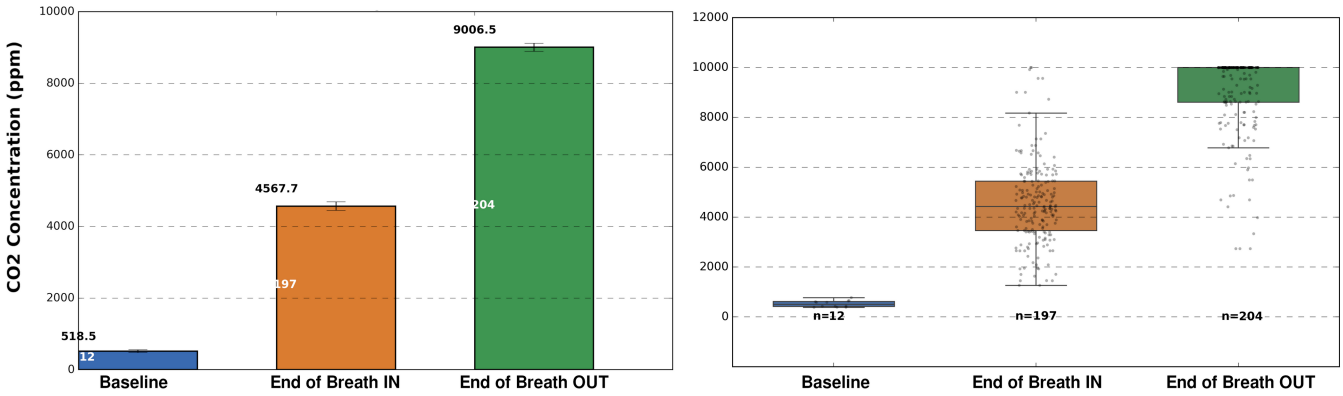

Figure 2: *CO_2 concentrations by respiratory phase shows the fluctuations in intra-mask CO_2 levels, demonstrating that N95 masks do not clear exhaled CO_2 rapidly enough to maintain ambient air quality inside the mask.*

Single vs. Double Mask Comparison

Contrary to initial hypotheses, no significant difference was found between single and double N95 masks in terms of intra-mask CO_2 retention. The results suggest that mask fit and seal, rather than the number of mask layers, dictate CO_2 retention.

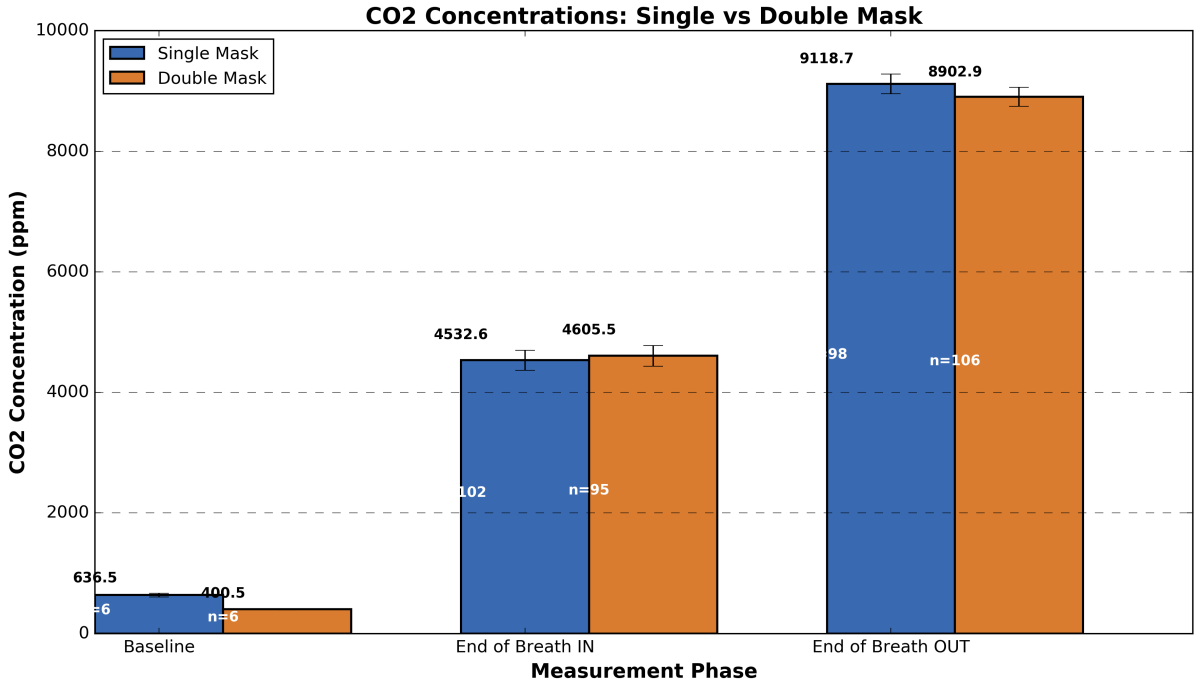

Figure 3: *CO_2 comparison of single vs. double mask.*

Measurement Phase	Single Mask (ppm) ± SD	Double Mask (ppm) ± SD	p-value
Baseline (Ambient Air)	636.47 ± 73.85	400.47 ± 0.00	0.0002
End of Inspiration	4532.58 ± 1745.29	4605.45 ± 1609.86	0.76
End of Expiration	9118.67 ± 1573.44	8902.87 ± 1628.19	0.34

Table 2: *CO_2 Levels in Single vs. Double N95 Masks*

Humidity and Temperature Effects

- Humidity inside N95 masks exceeded 90%, significantly higher than OSHA-referenced guidelines for acceptable workplace humidity (30%–60%) [2].
- A strong correlation between CO_2 and humidity (r = 0.87) suggests that moisture retention may contribute to wearer discomfort and mask effectiveness.

CO_2 Exposure Relative to OSHA Limits

This study provides a full-breath-cycle analysis of intra-mask CO_2 exposure, contrasting with previous studies that primarily measured CO_2 at the lowest inhaled concentration [3,4,6]. These findings confirm that wearers of N95 masks are exposed to CO_2 levels exceeding OSHA's 5000 ppm limit for most of the breath cycle, raising concerns about potential physiological effects in occupational settings requiring prolonged mask use.

These results establish strong evidence of CO_2 accumulation inside N95 masks and highlight the importance of considering full respiratory cycle dynamics when assessing potential risks of long-term mask wear.

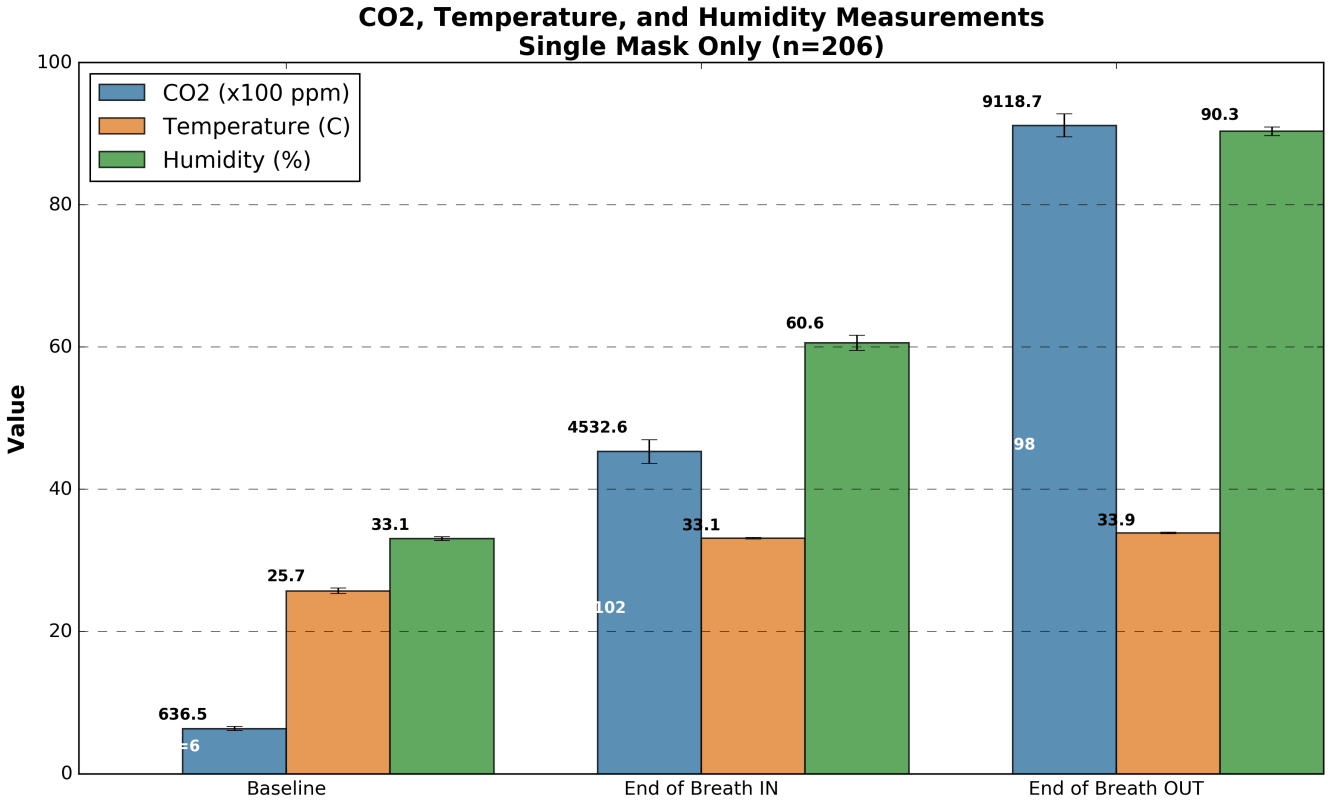

Figure 4: *Humidity inside N95 masks exceeded 90%, higher than OSHA-referenced guidelines for acceptable workplace humidity (30%–60%). A strong correlation between CO_2 and humidity (r = 0.87) suggests that moisture retention may contribute to wearer discomfort and mask effectiveness.*

Discussion and Conclusion

This study demonstrates that CO_2 accumulates significantly inside N95 masks, with intra-mask concentrations exceeding OSHA's permissible exposure limit (5000 ppm) for nearly the entire respiratory cycle. Peak CO_2 levels reached an average of 9006 ppm at end-exhalation, and even during inhalation, CO_2 levels remained elevated, only briefly dipping below 5000 ppm at the very end of a deep breath. These findings indicate that wearers continuously rebreathe air with CO_2 concentrations above occupational safety thresholds, a factor not fully accounted for in previous studies [3,4,6].

Despite initial concerns, no significant difference was found between single and double N95 masks, suggesting that CO_2 retention is dictated primarily by mask seal rather than the number of mask layers. Additionally, intra-mask humidity exceeded 90%, well above the OSHA-referenced comfort range (30%–60%) [2], reinforcing the strong correlation (r = 0.87) between CO_2 retention and moisture buildup.

These results challenge prior studies that focused solely on the lowest CO_2 concentration during inhalation, underestimating real exposure. While CO_2 accumulation at these levels is unlikely to cause acute harm in healthy individuals, prolonged exposure could contribute to symptoms such as headaches,

dizziness, or cognitive fatigue in occupational settings requiring extended mask use [5,7]. Future research should explore physiological impacts of prolonged N95 wear, particularly in high-exertion or long-duration use scenarios.

References

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