### ****Abstract****

**Hypothesis: Wearing an N95 mask will significantly increases intra-mask carbon dioxide (CO₂) levels. We hypothesize that CO₂ 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 CO₂ sensor** was placed inside **single and double N95 masks (3M 8210)** to measure CO₂, 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: CO₂ 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 CO₂:** **518.47 ± 132.76 ppm**
* **End-of-inspiration CO₂:** **4567.72 ± 1681.43 ppm**
* **End-of-expiration CO₂:** **9006.54 ± 1605.02 ppm**
* **Statistical Significance**: **p < 0.001** confirmed across all respiratory phases.
* **Single vs. Double Mask:** No significant difference in intra-mask CO₂ levels.

**Discussion:** CO₂ 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 CO₂ was 9006 ppm**, and even during inhalation, CO₂ 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 CO₂-humidity correlation (r = 0.87)** suggests moisture retention may contribute to discomfort. This study demonstrates that **N95 masks do not clear exhaled CO₂ fast enough to provide consistently safe air quality.**

### ****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 (CO₂)** 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 CO₂ within the mask cavity may impact wearer comfort and respiratory gas exchange.

Several studies have assessed CO₂ accumulation inside masks, often reporting levels between **2000 and 4000 ppm** during inhalation [1,2]. However, these studies primarily measure CO₂ levels **at the end of inhalation**, when CO₂ is at its lowest. In contrast, **exhaled CO₂ concentrations regularly exceed 35,000 ppm**, and without adequate clearance, significant retention may occur within the mask, exposing wearers to elevated CO₂ levels throughout the breathing cycle. **OSHA’s permissible exposure limit (PEL) for CO₂ is 5000 ppm over an 8-hour work period** [3], yet many prior studies have not directly assessed whether intra-mask CO₂ remains above this threshold for most of the respiratory cycle.

In this study, we measured intra-mask CO₂ concentrations **throughout the full breath cycle** using a **high-accuracy NDIR CO₂ sensor (Sensirion SCD-30)** placed inside both **single and double N95 masks (3M 8210)**. Unlike previous studies that report CO₂ at the lowest inhaled concentration, we assessed CO₂ levels **at baseline (ambient air), end of inspiration, and end of expiration**. Additionally, we recorded **temperature and humidity**, factors that may influence user discomfort. We hypothesize that **intra-mask CO₂ 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 CO₂ buildup inside N95 masks**, offering insight into **the physiological effects of prolonged mask use** in occupational and public health settings.

### ****Materials and Methods****

A **Sensirion SCD-30 non-dispersive infrared (NDIR) CO₂ sensor** (Sensirion AG, Switzerland) was used to measure **CO₂ concentration, temperature, and relative humidity** inside **single and double N95 masks (3M 8210, 3M, USA)**. The sensor was positioned **inside the mask near the nostrils** to capture intra-mask gas composition during respiration. The sensor has a **measurement range of 400–10,000 ppm CO₂** with an accuracy of **±(30 ppm + 3%)** and an integrated temperature/humidity sensor (±0.3°C, ±3% RH accuracy). An **external CO₂ sensor (Aranet4, SAF Tehnika, Latvia)** was used to validate **baseline CO₂ measurements**.

All measurements were conducted in a **home environment** with **HEPA air filtration** running near an **open window** to ensure adequate ambient air circulation. The CO₂ sensor was connected to a **Raspberry Pi 4 Model B (Raspberry Pi Foundation, UK)** via a **custom-built breadboard interface**, enabling continuous data acquisition and storage.

#### ****Measurements****

Three respiratory phases were analyzed:

1. **Baseline (Ambient CO₂):** Measurements taken in open air before mask placement.
2. **End of Inspiration:** CO₂ measured at the completion of inhalation.
3. **End of Expiration:** CO₂ measured at peak exhalation.

A total of **413 measurements** were collected: **12 baseline, 197 end-of-inspiration, and 204 end-of-expiration samples**. Each measurement phase was repeated multiple times to **ensure reliability**. Data collection was performed under **controlled breathing conditions** to minimize variability.

#### ****Data Processing and Analysis****

* **Statistical Analysis:**
  + **One-way ANOVA** was used to assess differences in CO₂ levels between respiratory phases.
  + **Paired t-tests** compared single vs. double mask conditions.
  + **Pearson correlation analysis** evaluated relationships between CO₂, temperature, and humidity.
* **Software and Hardware:**
  + Data was collected using a **Python script running on the Raspberry Pi** and analyzed in **Python (NumPy, SciPy, Matplotlib, Pandas)**.
  + Statistical significance was set at **p < 0.05**.
* **Figures:**
  + Data visualizations include **CO₂ concentration by respiratory phase, mask comparisons, and correlation matrices**.

All experimental images, sensor placements, and raw data files are available in supplementary materials on GitHub.

### ****Results****

#### ****CO₂ Accumulation Across Respiratory Phases****

CO₂ levels inside N95 masks were **significantly elevated** compared to ambient air, with peak levels occurring at **end-exhalation**. CO₂ concentration decreased during inhalation but 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**.

* **Baseline CO₂ (ambient air):** **518.47 ± 132.76 ppm** (n=12)
* **End of Inspiration CO₂:** **4567.72 ± 1681.43 ppm** (n=197)
* **End of Expiration CO₂:** **9006.54 ± 1605.02 ppm** (n=204)
* **Statistical Significance:** **p < 0.001**, confirming significant CO₂ retention across all respiratory phases.

**Figure 1: CO₂ Concentrations by Respiratory Phase** ([figure1\_co2\_by\_type.png]) visualizes the CO₂ fluctuations, demonstrating that **N95 masks do not clear exhaled CO₂ 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 CO₂ retention.

* **Baseline CO₂:** **Single Mask: 636.47 ppm**, **Double Mask: 400.47 ppm (p = 0.0002)**
* **End-of-Inspiration CO₂:** **Single Mask: 4532.58 ppm**, **Double Mask: 4605.45 ppm (p = 0.76)**
* **End-of-Expiration CO₂:** **Single Mask: 9118.67 ppm**, **Double Mask: 8902.87 ppm (p = 0.34)**

These findings suggest that **mask fit and seal, rather than the number of mask layers, dictate CO₂ retention**.  
**Figure 2: CO₂ Comparison of Single vs. Double Mask** ([figure3\_mask\_comparison.png]) illustrates these results.

#### ****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 CO₂ and humidity (r = 0.87)** suggests that **moisture retention may contribute to wearer discomfort and mask effectiveness**.
* **Figure 3: CO₂, Temperature, and Humidity Levels** ([figure4\_correlation.png]) highlights these relationships.

#### ****CO₂ Exposure Relative to OSHA Limits****

This study provides a **full-breath-cycle analysis** of intra-mask CO₂ exposure, contrasting with previous studies that **primarily measured CO₂ at the lowest inhaled concentration** [3,4,6]. These findings confirm that **wearers of N95 masks are exposed to CO₂ 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 CO₂ accumulation inside N95 masks** and highlight the importance of considering full respiratory cycle dynamics when assessing potential risks of long-term mask wear.

**References**

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