Experimental studies of carbon dioxide concentration in the space under the face mask protecting against Covid-19 – Pilot studies

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Abstract
Masks are the primary tool used to prevent the spread of COVID-19 in the current pandemic. The use of masks may result in some discomfort, which may be caused by the accumulation of carbon dioxide in the inner space of the mask. This paper presents tests of carbon dioxide concentration in the inner space of the mask during work at a computer, for various flat and convex masks. Five different masks were used in the tests. Convex masks showed a greater accumulation of carbon dioxide than flat masks. The concentration of carbon dioxide was also higher for masks made of more layers. The dependence of the average values of carbon dioxide concentrations under the masks for selected people depending on the BMI and the type of mask was determined, as well as the measurements of carbon dioxide concentrations without the mask. An increase in carbon dioxide concentration was observed with increasing BMI. The development of effective self-defense tools against the virus, including masks, is essential to contain the spread of COVID-19.

Keywords Face masks · COVID-19 · Carbon dioxide concentration · Air quality · Human health

Introduction
Indoor carbon dioxide (CO₂) is generated mainly by the breathing of people in the room [1–4]. According to the standards of the American Society of Heating, Refrigerating and Air-Conditioning Engineers [5], indoor air CO₂ levels should be well below 1,000 ppm to avoid the negative effects of poor indoor air quality [6–9]. A carbon dioxide concentration of 5,000 ppm (0.5%) is taken as the safety threshold for an eight-hour working day [10, 11]. According to various international standards, the recommended CO₂ concentration for good air quality for human breathing is in the range 600–1000 ppm, and the acceptable concentration is 1000–1400 ppm [5, 12–15]. Various health problems are observed with prolonged exposure of humans to the concentration of CO₂ above 5000 ppm. There are headaches, burning eyes and visual disturbances after fainting (with carbon dioxide concentrations above 70,000 ppm) and death (above 100,000 ppm) [14, 16]. In the literature [17, 18] there are studies describing the decline of intellect or disturbances of human concentration in unventilated rooms as a result of CO₂ accumulation in those rooms. In literature [18, 19] it was reported that people performing precise activities or learning become tired much faster as a result of an increase in the concentration of CO₂, while in [20] a deterioration in memorization scores was reported.

The coronavirus is an RNA virus covered with a fatty membrane, which can be combated with the use of chemicals such as ordinary soap, 60–70% alcohol, disinfectants and other virucidal preparations. COVID-19 is spread by talking, coughing, sneezing, and even breathing, in the form of aerosol droplets. Minimizing human-to-human spread of the virus is one of the most effective ways to control the current pandemic [21]. To prevent the spread of the disease, pharmaceutical interventions are undertaken, such as vaccinations and immune-boosting drugs, as well as non-pharmaceutical interventions such as social distancing, contact tracing, quarantine, face masks, regular hand washing with water, and the use of alcohol-based
disinfectants [22]. One of the non-pharmaceutical forms of protection against COVID-19 is the wearing of protective masks. Currently, masks are undergoing dynamic development with the use of modern technologies based, for example, on nanotechnology [23], and hybrid models using deep and classical machine learning are being developed to detect the presence of a face mask [24]. According to [21], the mask is a more effective method of controlling infection and breaking the COVID-19 transmission chain than other methods such as washing hands, personal hygiene and social distancing.

Wearing masks is one of the standard methods of preventing the spread of disease by droplets. The effectiveness of the use of protective masks has been the subject of many publications, mainly concerning health care [25–28]. Recent studies show that wearing masks should not adversely affect health [29, 30], even in people with diseases [31]. The results of studies in [32] show that wearing the N95 mask during low-intensity work (MET 3) may increase metabolism, which reduces exhaled oxygen and increases the concentration of exhaled CO₂.

Based on our own research [33] and literature [2, 3, 34, 35], we state that the concentration of CO₂ in a room depends primarily on: the volume of the room, the number of CO₂ sources and the intensity of ventilation (air exchange). A person exhales a different amount of CO₂ depending on activity. Table 1 shows the relationship between the quantity of carbon dioxide per person and the type of human activity.

The aim of the present study is to measure the concentration of CO₂ in selected masks while the user is working at a computer in a sitting position. Five different masks were used in the tests. It should be emphasized here that despite the fact that the introduction to the publication presents the influence of carbon dioxide on human health, no medical and questionnaire studies on the influence of carbon dioxide were used, including masks made by users themselves. The aim was to measure the concentration of CO₂ in the space bounded by the mask and face (the volume of the inner space of the mask).

### Description of the tested masks

The research was carried out on five different popular masks. They are shown in general view in Fig. 1a–e, and their technical parameters are given in Table 2. Mask 1 and masks 3–5 were bought in local stores in Poland, while mask 2 was made by the researcher from cotton material. Based on their shape, masks 1–3 (Fig. 1a–c) were classified as flat masks, while masks 4 and 5 were classified as convex masks. Based on the type of material on the face of the mask, they were further classified as homogeneous (masks 1–4) and heterogeneous (mask 5). The heterogeneous mask 5 (Fig. 1e) consists of unpainted material, painted material, and a centrally located check valve. In this mask, the check valve is designed to lower the temperature and humidity under the mask by increasing the air flow during exhalation, as a result of which unfiltered air is exhaled through the valve. During inhalation, the check valve closes. Unidirectional air filtration means that this mask exposes others to the risk of COVID-19 infection from the user of the mask. It should be noted here that during the COVID-19 pandemic, there was a rapid shortage of masks in shops and pharmacies, which is why at the beginning of the pandemic, various masks were used, including masks made by users themselves. The work examined the masks that were most often used in the first phase of the COVID-19 pandemic in Poland.

### Carbon dioxide measurements in the space between mask and face

Carbon dioxide measurements were made using a Testo IAQ probe connected to a Testo 435 recorder, for which the error is ±3% and ±5% of the measured value for the ranges 0–5000 ppm and 5001–+10,000 ppm respectively [33]. Before the experiment began, the apparatus was calibrated by an external calibration laboratory. The parameters of the internal and external environment were measured according to the recommendations given in the literature [37, 38]. Results were recorded every second. Carbon dioxide concentration was recorded every 1 s. The measurement point was located in the lower part of the zygomaticus major muscle (Fig. 2). The initial CO₂ value

![Image](https://example.com/image.png)

**Table 1** Carbon dioxide per person depending on activity level (own study based on [36])

| Activity                          | CO₂ CO₂ [dm³/h] | [g/h] |
|----------------------------------|-----------------|-------|
| Relax                            | 12              | 23.724|
| Activity level I (Sedentary)     | 15              | 29.655|
| Activity level II (Some physical activity) | 23              | 45.471|
| Activity level III (Moderate Physical Activity) | 30              | 59.31 |
| Activity level IV (Vigorous Activity) | above 30        | 59.31 |
was similar to the concentration of CO$_2$ in the room where
the tests were performed, and was on average 530 ppm.
The room in which the tests were carried out had a vol-
ume of 300 m$^3$ and was equipped with gravity ventilation
with 0.5 air changes. The average temperature in the
tested room was 21.3 °C (±0.1 °C). On each occasion
the mask was tested for 60 min, during which the people
using the masks performed light work at a computer in a

Table 2 Description of the tested masks

| Number | Name                  | Shape | Weight [g] | Material               | Description of the mask                                                                 |
|--------|-----------------------|-------|------------|------------------------|----------------------------------------------------------------------------------------|
| Mask 1 | three-layer mask      | flat  | 4          | non-woven polypropylene | type I, acc. to EN 14,683, three layers of fabric made of three layers of material       |
| Mask 2 | hand-made mask        | flat  | 14         | 100% cotton, weight: 125 g/m$^2$ | two layers of fabric                                                                  |
| Mask 3 | double-layer mask     | flat  | 4          | non-woven polypropylene | type FFP2 (according to EN 149: 2001 + A1: 2009 / GB2626-2006 KN95), mask equipped with a metal buckle at the level of the nose on the outer part of the mask, very densely woven materials, five layers of fabric |
| Mask 4 | protective mask, KN95 | convex| 5          | polypropylene           | half mask with an exhalation check valve, type FFP2 (according to EN 149: 2001), mask equipped with a metal clip at the level of the nose on the outer part of the mask, very densely woven materials |
| Mask 5 | filtering half mask, type FFP2 | convex | 14         | polypropylene           |                                                                                       |
sitting position. Carbon dioxide concentration measurements were made for four adults, whose characteristics are given in Table 3. Body mass index (BMI) was determined according to the following formula:

$$\text{BMI} = \frac{\text{weight}}{\text{height}^2},$$  \hspace{1cm} (1)

All masks were tested by four participants and each participant performed 10 measurement series for each mask. It should be noted here that the number of respondents is small and equals 4 people, and the age range of the respondents is narrow and ranges from 35 to 56 years, therefore the results of the research on CO₂ concentration presented in this paper should be treated as preliminary studies.

The uncertainty of the measured values was calculated according to Moffat [39] as follows:

$$\delta x = \sqrt{B_{\text{inst}}^2 - (2\sigma_{\text{ran}})^2},$$  \hspace{1cm} (2)

where $B_{\text{inst}}$ is the overall fixed error uncertainty of the measurement equipment, and $\sigma_{\text{ran}}$ is a random error caused by various factors.

Table 3 Characteristics of test subjects

| Number | Gender | Age | Height | Weight | BMI |
|--------|--------|-----|--------|--------|-----|
| Person 1 | female | 56  | 171    | 102    | 35  |
| Person 2 | male   | 43  | 180    | 90     | 28  |
| Person 3 | male   | 43  | 178    | 100    | 32  |
| Person 4 | female | 35  | 164    | 70     | 26  |

Results and discussion

Figure 3 shows the average values of CO₂ concentration for each mask and the measurement without mask measured for four people, from 10 measurement series for each mask. The highest mean values of CO₂ concentration were obtained for the convex masks (masks 4 and 5), and the lowest for the flat masks (masks 1, 2, 3). The lowest average concentration of CO₂ was obtained for the two-layer mask (mask 3), and was about one-sixth of the highest average concentration, obtained for the mask with a check valve (mask 5).

Table 4 shows the average values of CO₂ concentrations for various masks and test participants from 10 measurement series for each mask. The highest average values of CO₂ concentrations were recorded for the first participant of the study, the lowest values for the fourth participant. The maximum average concentration of carbon dioxide was recorded for person No. 1, which is the oldest in the studied group, while the minimum mean concentration of carbon dioxide was recorded for the youngest person (No. 4), which may indicate the influence of age on the concentration of carbon dioxide in the mask space. In order to achieve more accurate results, research should be carried out on a larger group of people.

In order to thoroughly understand the effect of the mask on the CO₂ levels in the space between the mask and the face, CO₂ concentration tests were performed without the mask with the CO₂ probe positioned in the same way as when measuring CO₂ with the mask. The results of the measurements are presented in Table 4 and Fig. 3. Table 4 also shows the average values of CO₂ concentration in the room where the tests were carried out. The values of CO₂ concentrations during the test without a mask are about 70%, 58%, 66%, 43% higher than the average CO₂...
concentration in the room for participant 1, 2, 3 and 4, respectively. Several dozen percent higher values of \( \text{CO}_2 \) concentrations during the measurement without the masks compared to the measurement of \( \text{CO}_2 \) concentration in the room indicate a significant effect of the \( \text{CO}_2 \) source, which is generated by the participant on the measuring probe. It should be noted here that the space of the mask is relatively small and it is probably impossible to eliminate this effect of the \( \text{CO}_2 \) source.

Figure 4a–e show example plots of \( \text{CO}_2 \) concentration under the mask over a period of one hour. The graphs show higher values of \( \text{CO}_2 \) concentration in the case of person 1 than person 2. The differences between the results of the tests between persons 1 and 2 indicate that the concentration of \( \text{CO}_2 \) under the mask may depend on individual characteristics of the user. In the case of convex masks (masks 4 and 5), greater fluctuations in the concentration of \( \text{CO}_2 \) were observed than in the case of flat masks. Drops in \( \text{CO}_2 \) concentration after reaching the maximum values in convex masks may be caused by respiratory compensation [40, 41]. Respiratory compensation aims to eliminate \( \text{CO}_2 \) and restore pH to normal levels by increasing alveolar ventilation [42]. The maximum instantaneous values of \( \text{CO}_2 \) concentrations were obtained for masks 4 and 5, and were about 10,000 ppm. It should be noted that, according to the literature [43], inhaled carbon dioxide at concentrations <10,000 ppm has practically no toxic effect.

Figure 5a–f show box plots for the exemplary series of \( \text{CO}_2 \) concentration measurements for masks 1, 2, 3, 4, 5, and measurement without the mask, respectively. The plots show a significant dispersion of data, which is probably related to respiratory compensation. The graphs also show significant outliers that are determined by the lower \( \text{CO}_2 \) concentration values when the \( \text{CO}_2 \) measurement is started, and upper outliers that are likely also due to respiratory compensation.

Figure 6 shows the dependence of the average values of \( \text{CO}_2 \) concentrations under masks for selected people depending on the BMI and the type of mask and measurements of \( \text{CO}_2 \) concentrations without mask. Figure 6 shows an increase in \( \text{CO}_2 \) concentration as BMI increases.

The average values of \( \text{CO}_2 \) concentration during work at a computer in the case of masks 1 and 4 were higher by approximately 20% and 45% respectively than the values of \( \text{CO}_2 \) concentration for the tested surgical mask and KN95 mask from [44]. Such significant differences in the results obtained for average \( \text{CO}_2 \) concentrations may result from the different research method used in [44], as well as from the individual characteristics of the person using the mask. In [44] the concentration of \( \text{CO}_2 \) in the breathing zone was determined by aspirating air through a silicone tube from

### Table 4  Average \( \text{CO}_2 \) concentrations for various masks and test participants from 10 measurement series for each mask

| Person  | Mask 1 | Mask 2 | Mask 3 | Mask 4 | Mask 5 | Measurement without mask | Inside the laboratory |
|---------|--------|--------|--------|--------|--------|--------------------------|-----------------------|
| Person 1 | 3514   | 2786   | 1515   | 5427   | 7334   | 914                      | 539                   |
| Person 2 | 2088   | 1875   | 976    | 3264   | 6525   | 835                      | 527                   |
| Person 3 | 2948   | 2592   | 1258   | 5201   | 6365   | 934                      | 563                   |
| Person 4 | 1964   | 1584   | 1196   | 2905   | 3914   | 754                      | 528                   |
the breathing zone behind the mask, where the sampling point was on the bridge of the nose, just above the tip. The placement of the inlet of the tube over the tip of the nose may cause additional fresh air intake through the face of the mask, and therefore the results for the CO₂ concentration in the mask may be understated.
Significant values of CO₂ concentration in N95 masks were obtained in [45], amounting to as much as 30,000 ppm. Such high values of CO₂ concentration are possibly influenced by the location of the probe between the nose and the mouth, which may result in the measurement of exhaled air, with a significant increase in the concentration of CO₂ during the measurement. In [46] high concentrations of CO₂ were also obtained in cloth and paper face masks.

Fig. 5 Examples of box graphs showing the concentration of CO₂ under the mask as a function of time in an hour for four people: a) mask 1, b) mask 2, c) mask 3, d) mask 4, e) mask 5, f) without a mask

Fig. 6 The dependence of the concentration of CO₂ under the masks depending on the BMI and the type of mask and CO₂ measurement without the mask
Conclusions

This paper has described measurements of carbon dioxide concentration in different masks. The following conclusions are drawn from the research:

1. The highest concentrations of carbon dioxide in the space between the mask and the face occurred for convex masks (7334 ppm), and the lowest for flat masks (976 ppm).
2. The greatest fluctuations in carbon dioxide concentrations were obtained for convex masks, which may be caused by respiratory compensation.
3. An increase in carbon dioxide concentration was observed with increasing BMI.

Due to the significant concentration of carbon dioxide in the mask space, it is worth considering the maximum period of use of the protective mask, followed by a break in wearing the mask. Introducing the maximum duration of use of the mask requires additional tests to be carried out in subsequent works.

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Declarations

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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