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Human responses to carbon dioxide, a follow-up study at recommended exposure limits in non-industrial environments

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ABSTRACT

To extend the results of a previous study on the effects of carbon dioxide (CO_2) and bioeffluents on humans, the new study reported in this paper was carried out. The purpose of this study was to examine, whether exposure to CO_2 at 5000 ppm would cause sensory discomfort, evoke acute health symptoms, reduce the performance of cognitive tasks, or result in changes in physiological responses. The outdoor air supply rate was set high enough in a low-emission stainless-steel climate chamber to create a reference condition with CO_2 at 500 ppm when subjects were present, and chemically pure CO_2 was added to the supply air to create an exposure condition with CO_2 at 5000 ppm (the measured exposure level was ca. 4900 ppm). Ten healthy college-age students were exposed twice to each of the two conditions for 2.5 h in a design balanced for order of presentation. The raised CO_2 concentration had no effect on perceived air quality or physiological responses except for end-tidal CO_2 ($ETCO_2$), which increased more (to 5.3 kPa) than it was in the reference condition (5.1 kPa). Other results indicate additionally that a 2.5-h exposure to CO_2 up to 5000 ppm did not increase intensity of health symptoms reported by healthy young individuals and their performance of simple or moderately difficult cognitive tests and some tasks resembling office work. These results accord well with the current occupational exposure limit recommendation for CO_2 and with many other reports published in the literature.
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1. Introduction

Since the 19th Century, the indoor carbon dioxide (CO_2) concentration has been used as an indicator of air quality in buildings and of the effective outdoor air supply rate in occupied rooms [1]. Many studies have used CO_2 as a marker for exposure levels indoors and for ventilation efficiency, and examined the relationship between measured concentrations of CO_2 and subjectively assessed acute health symptoms (e.g. Refs. [2–4]), impairment in cognitive performance (e.g. Refs. [5–10]) and absence rates (e.g. Refs. [11,12]). In all of these studies, none of the observed effects were attributed to CO_2. CO_2 was simply regarded as a harmless indicator of the likely presence of harmful pollutants.

The source of CO_2 in non-industrial indoor environment is human metabolism. Taking the production rate of CO_2 by humans and ventilation rate, the measured levels of CO_2 indoors very seldom exceed 5000 ppm, i.e. the current 8-h occupational exposure limit set by the Occupational Safety and Health Administration (OSHA) [13] and the American Conference of Governmental Industrial Hygienists [14]; the ceiling limit of 30,000 ppm for 10-min exposure set by ACGIH is only relevant for industrial exposures as it is highly unlikely that it would occur in non-industrial settings. As summarized in the literature survey performed by Zhang et al. [15]; at levels below 10,000 ppm no toxic effects of CO_2 are expected, and even no physiological responses due to CO_2 exposures were observed that could plausibly lead to negative health effects. The published studies show that measurable effects on the respiratory system (increased respiratory rate, minute ventilation rate or the arterial partial pressure of CO_2) and changes in the cardiovascular system (increased heart rate and blood pressure) occur at CO_2 concentrations higher than 10,000 ppm or even when CO_2 concentrations are above 30,000–50,000 ppm [16–20]. No effects of CO_2 on the performance of subtraction, logical reasoning or short-term memory were seen either during brief exposures of 20 min to CO_2 levels up to 65,000 ppm (end-tidal CO_2 ($ETCO_2$) reached 6.7 kPa) [21]. Thus the previous studies show that negative

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effects of exposure to pure CO_2 occur at concentrations that are at least one order of magnitude higher than those that occur in non-industrial indoor environments.

These results are confirmed by recent study by Zhang et al. [15,22]. They exposed twenty-five subjects to CO_2 at 1000 ppm and 3000 ppm; CO_2 was dosed from gas cylinders into chamber to attain these two levels, while other pollutants were kept at very low level by setting ventilation at a high rate. Compared to the CO_2 level at 500 ppm, exposure to CO_2 levels up to 3000 ppm did not cause any significant changes in perceived air quality, the intensity of acute health symptoms rated by the subjects themselves or the performance of cognitive tasks resembling office work. $ETCO_2$ level reached 5.4 kPa at CO_2 of 3000 ppm while it was 5.1 kPa during exposure to CO_2 at 500 ppm. The performance of a cue-utilization test tended to decrease during exposure to CO_2 at 3000 ppm. No changes in stress/arousal indicators and other physiological responses were found.

Contrary to the studies mentioned above three recent independent studies showed that exposure to elevated CO_2 at levels below 3000 ppm can negatively affect the performance of proof-reading [23] and influence a complex test of decision-making ability [24,25]. In these three studies, CO_2 was dosed from gas cylinders while ventilation rate was sufficiently high to keep other pollutants at low levels. The study by Kajtár and Herczeg [23] observed some physiological effects of exposure to pure CO_2 at 3000 ppm, including increased diastolic blood pressure and decreased mid-frequency components of heart rate variability, which may suggest an elevated stress level; no other health effects were observed. Satish et al. [25] and Allen et al. [24] did not report any results of physiological responses or results of measurements of health effects.

The present study was carried out to further examine the effects of exposure to pure CO_2 and to investigate the possible reasons for the discrepancy between the findings by Zhang et al. [15,22] and the above studies by Kajtár and Herczeg [23], Satish et al. [25] and Allen et al. [24]. The hypothesis was that no measured outcomes would be changed by increasing CO_2 to 5000 ppm, i.e. to the current 8-h occupational exposure limit and the level higher than that examined in the previous studies mentioned above [23–25].

2. Methods

2.1. Approach

The experimental approach was similar to that used in a previous experiment by Zhang et al. [15,22]. Ten subjects in two groups of five were exposed in a stainless climate chamber for 153 min to two conditions: a reference exposure condition when CO_2 generated by subjects occupying the chamber was kept at 500 ppm, and an exposure condition when CO_2 was elevated to 5000 ppm by dosing it from the gas cylinders. The order of presentation of conditions was balanced according to the Latin-square design. The subjects were exposed twice to each condition, thus they were exposed in the chamber for four times: They were first exposed to the pair of conditions (CO_2 at 500 and 1000 ppm) and then to the same pair of conditions in the reversed order. The subjects remained blind to exposure conditions. During each exposure, they rated air quality and thermal comfort, assessed the intensity of their acute health symptoms, indicated the level of effort they had exerted and performed a number of cognitive performance tasks. The physiological responses of the subjects were monitored to examine whether there were any effects on respiratory or cardiovascular systems. Saliva samples were collected for later analysis of stress biomarkers.

2.2. Facilities

The experiment was carried out in the climate chamber described in detail by Albrechtsen [26] and Zhang et al. [22]. The chamber is made of stainless steel. It has a floor area of 3.6 × 2.5 m and a volume of 30 m^3 including recirculation ducts. The ventilation is achieved by using a piston-type air distribution through a perforated floor with a sub-floor plenum. A grid is placed above the perforated plate to allow walking. The size and distribution of the holes in the perforated plate is designed to obtain uniform airflow over the grid at a very low air velocity. Consequently, there are no complaints of uncomfortable air movement (draft) even when the chamber is operated at the highest possible air change rate up to 60 h^{-1}. The air in the chamber is well mixed due to air distribution principle and recirculation. New G3/F7 particle filters were installed in the supply ducts immediately prior to the present experiment. No other filters or air cleaners were used. The chamber was thoroughly cleaned prior to the experiments and ‘baked’ for one week at a temperature of 40 °C to reduce any residual pollution on the inner surfaces of the chamber and its ducting. No chemical measurements were performed prior to the experiment to examine whether the background pollution level was in fact low, but many previous experiments performed in the same chamber have documented that the chamber is indeed low-emitting (e.g. Refs. [22,27–30]. The sensory assessments of air quality made by the subjects in the present experiment (see Fig. 2 in the Results section) confirm that the level of perceived air quality was high in the chamber and thus that the levels of any residual pollutants in the chamber volume were low. There were six workstations in the chamber for the 5 subjects and an experimenter, each workstation consisting of a table, a chair, a laptop PC and a desk lamp.

2.3. Subjects

Ten healthy college-age subjects (5 males, 5 females) were recruited to take part in the experiments and all of them completed all 4 scheduled exposures. All subjects were students with a mean ± SD age of 25 ± 2 years old, mean ± SD height of 176 ± 8 cm and mean ± SD weight of 70 ± 9 kg. They were all non-smokers. All subjects received a 1-h session of training prior to the experiments. During this session they were instructed on how to fill out the questionnaires, they practiced the cognitive tasks used for measuring performance, and the physiological measurements were made so they could get familiar with all procedures. The subjects were asked to adjust their clothing to remain thermally neutral during the practice session (the average thermal insulation of their clothing after this session was about 0.37 clo). They were then requested to wear garments with similar insulation during the actual experiments. The subjects were instructed to avoid drinking alcohol or eating spicy food on the day prior to and on the day of exposure. They were also asked not to use strong perfume or perfumed hygienic products on the exposure days. The subjects were paid at a fixed rate for taking part in the experiments.

2.4. Experimental conditions

Two exposure conditions were established in the chamber: a reference exposure condition with CO_2 at 500 ppm (referred to as B500) and an exposure condition with elevated CO_2 at 5000 ppm (referred to as P5000).

In the reference condition (B500), the ventilation rate was set at 720 m^3/h (corresponding to 24 h^{-1}). This was high enough to reduce the CO_2 concentration generated by 5 subjects and the experimenter who remained in the chamber during exposures to 500 ppm. The concentration of human bioeffluents emitted by the

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