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Effects of low-level inhalation exposure to carbon dioxide in indoor environments: A short review on human health and psychomotor performance

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ABSTRACT

Scientific literature and documents pertaining to the effects of inhalation exposure to carbon dioxide (CO_2) on human health and psychomotor performance were reviewed. Linear physiological changes in circulatory, cardiovascular, and autonomic systems on exposure to CO_2 at concentrations ranging from 500 to 5000 ppm were evident. Human experimental studies have suggested that short-term CO_2 exposure beginning at 1000 ppm affects cognitive performances including decision making and problem resolution. Changes in autonomic systems due to low-level exposure to CO_2 may involve these effects. Further research on the long-term effects of low-level CO_2 exposure on the autonomic system is required. Numerous epidemiological studies indicate an association between low-level exposure to CO_2 beginning at 700 ppm and building-related symptoms. Respiratory symptoms have been indicated in children exposed to indoor CO_2 concentrations higher than 1000 ppm. However, other indoor comorbid pollutants are possibly involved in such effects. In the context of significant linear increase of globally ambient CO_2 concentration caused by anthropogenic activities and sources, reducing indoor CO_2 levels by ventilation with ambient air represents an increase in energy consumption in an air-conditioned building. For the efficient energy control of CO_2 intruding a building from ambient air, the rise of atmospheric CO_2 concentration needs to be urgently suppressed.

1. Introduction

Carbon dioxide (CO_2) is a colorless, tasteless, odorless, and non-flammable gas that is heavier than air and may accumulate at lower spaces, causing a deficiency of oxygen (IPCS, 2006). It is naturally present in the earth's atmosphere as a trace gas and a product of cellular respiration or fossil fuel burning (van Groenigen et al., 2011). The typical outdoor CO_2 concentrations are approximately 380 ppm, although in urban areas these have been reported to be as high as 500 ppm because of the increased anthropogenic sources (Persily, 1997). The increasing CO_2 concentration contributes to the greenhouse effect and accelerates global warming (Bertoni et al., 2004; Cox et al., 2000). According to the World Meteorological Organization, the globally averaged CO_2 concentration in the atmosphere has reached the symbolic and significant milestone of 400 ppm for the first time in 2015 (WMO, 2016) and has risen to 403.3 ppm in 2016 (WMO, 2017). The mean annual absolute increase during the last 10 years was 2.2 ppm per year (WMO, 2017). Simulated multi-models project the atmospheric average CO_2 concentrations to range between 794 and 1142 ppm by 2100 (IPCC, 2013).

The main source of CO_2 in the non-industrial indoor environment is human metabolism, although an increase in the ambient CO_2 concentration will also contribute to an increase in the indoor CO_2 concentration (Alberts, 1994). In addition, the need to reduce energy consumption provides an incentive for low rates of ventilation, leading to higher indoor CO_2 concentrations. The indoor CO_2 concentration represents an indicator of indoor air quality acceptability, air flow exchange suitability, and whether there is sufficient fresh air within

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indoor spaces in buildings (Emmerich and Persily, 2001). The typical average indoor CO_2 concentration ranges from 800 to 1000 ppm (NRC, 2008). National indoor air quality guidelines have established an upper limit of 1000 ppm for CO_2 concentrations in non-industrial buildings in Japan (NRC, 1981); Canada (Health Canada, 1995); Singapore (MOE, 1996); Norway (Becher et al., 1999); China (Peng et al., 2017); South Korea (Oh et al., 2012); Germany (Lahrz et al., 2008); and Taiwan (Chen et al., 2016).

Ventilation with ambient air is frequently used for reducing indoor CO_2 concentration. However, when low-level inhalation of CO_2 affects human health, the outdoor air flow rate by ventilation must be further increased to both maintain an acceptable indoor CO_2 concentration and to adapt to the increasing outdoor atmospheric CO_2 concentration, and a further step would involve the installation of an indoor CO_2 purification system within the ventilation system, leading to a tremendous increase in the energy load of buildings.

Lastly, the effects of low-level CO_2 exposure on human health should be re-examined in light of the current trend of increasing outdoor atmospheric CO_2 concentration. Herein we report a review of current literature pertaining to the association of low-level CO_2 exposure in non-industrial buildings with human health and related human responses.

2. Data collection

An online literature search was conducted across major electronic databases, including PubMed, Google Scholar, CiNii, and J-Dream III, between 1950 and June 11, 2018. PubMed was primarily used to identify potential articles that qualified the search criteria, and others were used as complementary databases. The following key words were used as search criteria: "carbon dioxide" AND health AND effect; "carbon dioxide" AND sick AND building; indoor AND "carbon dioxide" AND health. A total of 1475 articles were retrieved. After exclusion of duplicate publications, the retrieved articles were reviewed by a reviewer (KA) in two stages: screening of titles and abstracts, followed by full-text review. Additional articles were identified based on prior knowledge (e.g., documents or reports of international or national organizations) and by manual screening of the bibliographies of the retrieved articles. A total of 99 full-text articles were reviewed. Only peer-reviewed articles pertaining to original research or review of experimental or human studies directly associated with health and related response to exposure to CO_2, which clearly identified the air concentration of CO_2, were considered. Useful comprehensive review articles in conference proceedings were carefully considered along with the cited references. Studies focusing on poor ventilation, medical treatment, and physical exercise were excluded. The search was updated on August 19, 2018.

3. Biological effects

CO_2 is produced by intracellular metabolism in the mitochondria. The amount produced depends on the metabolism rate and the relative amounts of carbohydrates, fats, and proteins metabolized. As CO_2 accumulates in the blood, the blood pH decreases (acidity increases). Therefore, CO_2 is discharged from the human body for maintaining the acid–base balance in the blood (Geers and Gros, 2000). The CO_2 produced within the cells is transported into the blood (internal respiration) and is carried by the blood through the venous system to the lungs where CO_2 passes from the blood into the lung alveoli to be exhaled into ambient air (external respiration) (Lifson et al., 1949).

Lowering the pH or raising the partial pressure of CO_2 (pCO_2) releases of oxygen (O_2) from oxyhemoglobin (Arthurs and Sudhakar, 2005). An increase of pCO_2 delivered to the lungs, that is, hypercapnia, induces an increase of pCO_2 in the alveoli. CO_2 freely diffuses through the alveolar membrane and into the blood, resulting in an increase of CO_2 tension in arterial blood ($PaCO_2$). In turn, this increase in $PaCO_2$ (lower blood pH) results in an acute or chronic respiratory acidosis caused by the acid–base imbalance in the blood (Guais et al., 2011).

Respiratory acidosis corresponds to CO_2 accumulation. Acute or acutely worsening chronic respiratory acidosis causes headache, confusion, anxiety, drowsiness, and stupor (CO_2 narcosis). Slowly developing, stable respiratory acidosis may be well tolerated, but could result in memory loss, sleep disturbances, excessive daytime sleepiness, and personality changes. CO_2 rapidly diffuses into the brain across the blood–brain barrier. Symptoms and signs are the result of high CO_2 concentrations (low central nervous system pH) in the central nervous system and any accompanying hypoxemia (Porter et al., 2011).

Respiratory acidosis appears by definition from exposure to a CO_2 concentration of 10,000 ppm for at least 30 min in a healthy adult with a moderate physical load (DFG, 2012). An increase in the inhaled CO_2 concentration can result in increased respiratory rate, metabolic stress, increased brain blood flow, and increased minute ventilation (above 10,000 ppm); decreased exercise tolerance in workers when breathing against inspiratory and expiratory resistance (above 30,000 ppm); headache, dizziness, confusion, and dyspnea (above 50,000 ppm); sweating, dim vision, vomiting, disorientation, hypertension, and loss of consciousness (above 100,000 ppm) (ACGIH, 2017; HSDB, 2015; Rice, 2003).

4. Effects of low-level exposure to CO_2 in humans

According to traditional knowledge, although physiological studies showed that CO_2 raises the respiration rate increases above the level required for gas exchange, imposing an additional load on the respiratory system at concentrations higher than 5000 ppm, Pettenkofer and Flügge had proposed in 1881 that 700–1000 ppm should be regarded as the permissible indoor CO_2 concentration, indicating an indirect index of the contamination of air in buildings, which criteria had no physiological basis (Goromosov, 1968). A study in human subjects reported that inhalation exposure to 1000 ppm CO_2 for a short term caused marked changes in respiratory movement amplitude, peripheral blood flow increases, and the cerebral cortex functional state. While 1000 ppm CO_2 in the air reportedly has a directly harmful effect on humans, no detailed experimental methods and analyses were provided (Eliseeva, 1964). Thus, the association of CO_2 exposures at concentrations lower than 5000 ppm and human health remained very limited in the 1960s.

4.1. Building-related symptoms

Building-related symptoms (BRSs), commonly called sick building syndrome, are defined as symptoms that are experienced within the building but improve when away from the building (Redlich et al., 1997). Symptoms assessed are related to the upper and lower respiratory tract, eyes, and skin and include headache, fatigue, and difficulty concentrating (Finnegan et al., 1984). A comprehensive review of 21 studies reported that around half suggest that the risk of BRSs continues to diminish significantly with CO_2 concentrations decreasing to lower than 800 ppm (Seppänen et al., 1999). According to the Building Assessment Survey and Evaluation (BASE) study conducted in the U.S.A., significant associations of mucous membrane and lower respiratory symptoms with increasing indoor minus average outdoor CO_2 (dCO_2)(100 ppm increase) and maximum indoor 1 h moving average CO_2 minus outdoor CO_2 concentrations (250 ppm increase) were observed when workday average CO_2 concentrations remained lower than 800 ppm (1579 participants of 33 U.S. Office buildings) (Apte et al., 2000; Erdmann and Apte, 2004). In a longitudinal study conducted following the BASE study, upper respiratory symptoms were significantly associated with increased indoor CO_2 levels (98 participants of 21 Offices). However, the relationship between CO_2 concentrations and upper respiratory symptoms in this study was no longer statistically significant after adjusting for the number of people in the