THE INFLUENCE OF LOW CONCENTRATIONS OF INSPIRED CARBON DIOXIDE ON SOME PHYSIOLOGICAL PARAMETERS AT MODERATE PHYSICAL WORK

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ABSTRACT

Six young coal miners were exposed to laboratory conditions, roughly identical with those existing in a coal-mine. The climate was maintained at an ET of 20 °C, while the subjects performed intermittent moderate work on a bicycle. They inhaled different mixtures of air and CO$_2$ by a closed circuit method, where the CO$_2$ concentrations varied from 0.03 to 3.0 vol% for a constant climate, two different dynamic loads (360 and 450 kpm min$^{-1}$) and six different concentrations of CO$_2$ in the inspired air gave rise to 12 possible combinations, each of which was repeated twice in a series at random.

During the experiment many physiological parameters were measured such as heart frequency, tidal volume, breathing minute volume, oxygen uptake, carbon dioxide expired, alkali reserve, rectal temperature, skin temperature and subjective rating of fatigue.

First, V increased with increasing CO$_2$ imp. At a lower physical load (300 kpm min$^{-1}$) there was a greater increase of V due to $V_T$, whereas an augmented physical load (of 450 kpm min$^{-1}$) led to a greater increase of V due to $f_v$. This may partly be due to a decreased concentration of O$_2$ imp, but the main cause remains the increase in the CO$_2$ imp concentration. The oxygen uptake increased with increasing CO$_2$ imp. This can be explained as a consequence of a greater activity in the respiratory muscles. A portion of CO$_2$ imp is retained in the body, whereas the alkali reserve in the venous blood remains within physiological limits. Other physiological parameters ($\delta p$, $t_{rc}$, $k_x$, SRF) did not show any significant correlation with increased concentrations of CO$_2$ imp.

Summarizing the effects of low concentrations of CO$_2$ in the inspired air at moderate physical work, concentrations of CO$_2$ imp not exceeding 1.5 vol% in the inspired air were found to be tolerable.

In modern coal-mining using coal-cutting machines considerable amounts of carbon dioxide and methane tend to escape. The CO$_2$ concentration sometimes exceed 5 vol%, the MAC in Yugoslavia being 0.5 vol%. The vital question arises, whether work in such environmental conditions, at the usual effort and in the usual shifts, is still tolerable.
SUBJECTS AND METHODS

A previous study dealing with the miner's work place was used to work out a programme for the laboratory experiment. Climatic conditions roughly identical with those met in mines were provided by a climatic chamber and maintained at an external temperature of 20 °C (Fig. 1). The subjects, i.e. six young miners, were volunteers, motivated partly by their own problem and

![Diagram](image)

**FIG. 1** - Design of the equipment: 1. room air, 2. electric fan, 3. container with CO₂, 4. valves and pressure gauges, 5. gas mixing chamber, 6. servo motor for opening and closing of the valve, 7. regulator of the CO₂ concentration, 8. automatic analysis of CO₂ concentration, 9. container for the gas mixture, 10. ventilation (breathing) valve, 11. drop off of condensed water vapour, 12. and 13. ventilation rate counter, 14. gasometer, 15. a sample of the expired air.

**TABLE 1**

Data on volunteers taken in the experiment.

<table>
<thead>
<tr>
<th>Age</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>Mean circumference</th>
<th>Thorax (cm)</th>
<th>Abdomen (cm)</th>
<th>Maximal aerobic capacity (1 min⁻¹)</th>
<th>Vital capacity (cm³)</th>
<th>FEVS (cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>175.5</td>
<td>71.3</td>
<td>99.0</td>
<td>83.0</td>
<td>3.20</td>
<td>5500</td>
<td>3960</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>175.0</td>
<td>77.5</td>
<td>101.0</td>
<td>88.0</td>
<td>3.40</td>
<td>5620</td>
<td>4120</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>176.5</td>
<td>72.5</td>
<td>90.5</td>
<td>87.0</td>
<td>2.60</td>
<td>5140</td>
<td>4700</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>174.0</td>
<td>66.0</td>
<td>90.0</td>
<td>84.0</td>
<td>2.30</td>
<td>5500</td>
<td>3700</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>176.5</td>
<td>73.0</td>
<td>94.5</td>
<td>78.0</td>
<td>4.10</td>
<td>4900</td>
<td>4180</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>180.0</td>
<td>67.5</td>
<td>90.0</td>
<td>79.0</td>
<td>2.95</td>
<td>5150</td>
<td>4250</td>
<td></td>
</tr>
</tbody>
</table>

X 25.7 176.3 71.3 94.2 82.7 3.1 5301.7 4151.7

S.D. 5.09 2.07 4.13 4.87 3.50 0.63 279.46 332.53
partly by the payment offered for the participation. Table 1 lists some personal data of the miners. In that study we found a mean oxygen uptake of about 0.8–1.11 min⁻¹ at a ventilation of 23–311 min⁻¹ during the intermittent work. On this basis the experimental load was planned consisting of cycling on the ergometer in twelve cycles of 12 minute work and 3-minute rests. The daily alternated load was 300, or 450 kpm min⁻¹. The subjects inhaled a mixture of air and CO₂ in a close circuit in the following concentrations (vol%): 0.03, 0.5, 1.0, 1.5, 2.0 and 3.0. The increased amount of CO₂ in the mixture caused diminishment of O₂ concentration similar to the atmosphere in a coal mine. Assuming a constant climate at two alternating dynamic loads and six different CO₂ imp concentrations, 12 possible combinations presented themselves each of which was repeated twice in a series at random.

The parameters heart frequency (f_H), tidal volume (V_T) and breathing minute volume (V) were recorded every three minutes and expressed as a mean of the cycle (12-minute work plus 3-minute rest). After each cycle the end values of the rectal temperature (t_re), skin temperature (t_s) on the manubrium sterni and subjective rating of fatigue (SRF) were measured on a scale ranging from 0–100. Gas samples of the expired air were taken after the first, fifth, seventh and eleventh cycle. Concentrations of CO₂ and O₂ were analysed according the Schollander’s method and corrected to STPD conditions. Samples of the venous blood were taken after cycles 5 and 11. The alkali reserve was analysed according to the method of van Slyke.

RESULTS AND DISCUSSION

With increasing CO₂ imp concentration in the inspired air, the concentrations of O₂ imp decreased according to the following equation:

\[ O_2 \text{ vol}\% = -0.22 \times CO_2 \text{ vol}\% + 20.61 \]

Thus the subjects inhaled a lower concentration of O₂ at a higher concentration of CO₂ imp.

Cycles 5 and 11 appeared to be the most representative for a further analysis. First, the V increased according to the increased CO₂ imp in the form of a linear regression:

- V 1 min⁻¹ = 4.86 CO₂ imp vol% + 19.17 E 1/5/300
- V 1 min⁻¹ = 4.97 CO₂ imp vol% + 18.06 E 1/5/300
- V 1 min⁻¹ = 4.66 CO₂ imp vol% + 23.51 E 1/5/450
- V 1 min⁻¹ = 4.25 CO₂ imp vol% + 23.42 E 1/5/450,

where I/II means the first or the repeated series, 5 the fifth cycle, and 300 and 450, respectively the load in kpm min⁻¹.

No significant difference was established either between the first and the second series, or between the fifth and eleventh cycle, which confirms a stable physiological response (Fig. 2).

V 1 min⁻¹ represents a product of the breathing frequency (f_v) and V_T. At 300 kpm min⁻¹, V_T was observed to cause a greater increase in V, whereas at 450
kpm min⁻¹ V increased to a greater extent due to f₁ (Figures 3 and 4). When augmenting the dynamic load, we observed an increased dependency of the V increase on f₁.

Menn and co-workers³ report however, that at submaximum work and an increased concentration of CO₂ inst V depends more upon V̇₁. Bannister and co-workers⁴ attribute the increase of V in dynamic work and in conditions of a higher concentration of CO₂ inst not only to an increased pCO₂ but also to a lowered concentration of pO₂ and a lowered threshold of the respiratory center to CO₂ respectively, resulting from acidosis and changes of body temperature.

As stated above, in our experiment the concentration of O₂ inst decreased with increasing concentration of CO₂ inst which partly explains the effects reported. On the other hand, there is no correlation between tre and increased V.

The O₂ uptake increased with increasing of CO₂ inst in a linear way. The following regression equations were found:

\[
\begin{align*}
    & O_2 \text{ 1 min}^{-1} = 0.017 \text{ vol}\% \text{ CO}_2 \text{ inst} + 0.92 & E. & 1/5/300 \\
    & O_2 \text{ 1 min}^{-1} = 0.041 \text{ vol}\% \text{ CO}_2 \text{ inst} + 0.84 & E. & 1/5/300 \\
    & O_2 \text{ 1 min}^{-1} = 0.039 \text{ vol}\% \text{ CO}_2 \text{ inst} + 1.09 & E. & 1/5/450 \\
    & O_2 \text{ 1 min}^{-1} = 0.025 \text{ vol}\% \text{ CO}_2 \text{ inst} + 1.10 & E. & 1/5/450,
\end{align*}
\]
FIG. 3 - On the abscissa volume CO₂ in the inspired air, on the ordinate the tidal volume Vₜ l. For description see Figure 1.

FIG. 4 - On the abscissa volume CO₂ in the inspired air, on the ordinate the ventilation (breathing) frequency per minute. For description see Figure 1.
where 1/II means the first or the repeated series, 5 the fifth cycle, 300 and 450 respectively the load in kpm min\(^{-1}\).

Menn and co-workers\(^3\) dispute such an increase of O\(_2\) uptake which, however, is supported by Craig\(^2\). The increase might be due to an increased activity of the respiratory muscles with increasing V.

A portion of CO\(_2\) \text{insp} is retained in the body, following the equations:

\[
\begin{align*}
Y_{300} &= 0.329x - 0.03 \\
Y_{450} &= 0.336x + 0.07
\end{align*}
\]

where y is the gMol CO\(_2\) retained per hour, and x the vol\% CO\(_2\) \text{insp}, while 300, and 450, respectively are the dynamic loads expressed in kpm min\(^{-1}\) (Fig. 5).

The question arose as to what happens with the CO\(_2\) retained. As is well known, CO\(_2\) is mainly transported by the blood as bicarbonate, in a smaller proportion only as carbonic acid or solved gas, and as carboxy haemoglobin. It can, of course, also enter the synthesis of organic molecules. The increased retention of CO\(_2\) was anticipated to change the alkali reserve, but it remained within the physiological limits throughout the experiment (Table 2). As regards the other measured parameters (f\(_H\), t\(_R\), t\(_S\), SRF) these did not show any significant correlation with increased concentration of CO\(_2\) \text{insp}. Summarizing the effects of low concentrations of CO\(_2\) \text{insp} at moderate physical work, concentrations of CO\(_2\) \text{insp} up to 1.5 vol\% in the inspired air may be considered risk-free.

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**FIG. 5** – On the abscissa vol\% CO\(_2\) in the inspired air, on the ordinate the amount of the CO\(_2\) retained in g mol per hour. The upper regression line refers to the exercise 450 kpm min\(^{-1}\), the regression line beneath refers to the exercise 300 kpm min\(^{-1}\).
TABLE 2
Mean alkali reserve in the venous blood at different concentrations of
CO₂ in the inspired air and at two different dynamic loads.

<table>
<thead>
<tr>
<th>vol% CO₂ resp</th>
<th>300 kpm min⁻¹</th>
<th>450 kpm min⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.03</td>
<td>49.28</td>
<td>48.80</td>
</tr>
<tr>
<td>0.5</td>
<td>52.65</td>
<td>53.76</td>
</tr>
<tr>
<td>1.0</td>
<td>58.24</td>
<td>56.00</td>
</tr>
<tr>
<td>1.5</td>
<td>71.23</td>
<td>58.70</td>
</tr>
<tr>
<td>2.0</td>
<td>47.04</td>
<td>56.82</td>
</tr>
<tr>
<td>3.0</td>
<td>53.76</td>
<td>56.00</td>
</tr>
</tbody>
</table>

REFERENCES