Ventilatory Response to Carbon Dioxide during Moderate Exercise

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Abstract: Ventilatory Response to Carbon Dioxide during Moderate Exercise: Masayoshi Takahashi, et al. National Institute for Resources and Environment—Elevated carbon dioxide (CO2) concentration is one of the most important physiological stressors with closed-circuit breathing-apparatus (CCBA). We determined the ventilatory response to CO2 during moderate exercise by measuring the relationship between VE and PETCO2. Based on our findings, it is recommended that the permissible inhaled CO2 limit for CCBA in the Japan Industrial Standard (JIS) be lowered from 3% to 2%, and that the members of a rescue or fire fighter team who use CCBA be selected on the basis of their ventilatory sensitivity to CO2.

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Key words: Carbon dioxide, Ventilatory response, Steady-state method, Moderate exercise, Closed-circuit breathing-apparatus, Japan Industrial Standard

Closed-circuit breathing-apparatuses (CCBAs) are important tools for rescue and escape activities in an irrespirable atmosphere. But the apparatus inherently impose several physiological stressors, with elevated inhaled carbon dioxide (CO2) concentrations being one of the most important. The increase in ventilation rate due to the CO2 stimulus is the most significant concern for CCBA designers and government certifying agencies, since this results in higher breathing pressure, which is another CCBA stressor. Read’s rebreathing technique1 is the most common method for evaluating a person’s ventilatory response to CO2 at rest. Some research studies use this method during exercise2-4. But there are several problems inherent in the use of this technique during exercise, such that the effect of exercise on the response may not be correctly evaluated. In order to ensure the safe performance of CCBA at moderate to high work rates, the ventilatory response to CO2 during exercise is important in deciding the appropriate permissible level of inhaled CO2. The purpose of the study is to determine the effect of exercise on the ventilatory response, and to evaluate the appropriateness of the permissible level of the inhaled CO2 concentration for CCBA.

Methods

Steady-state CO2 inhalation was employed to measure the ventilatory response. Figure 1 shows a schematic diagram of the system, which continuously measured the subject’s ventilation rate and end-tidal CO2 concentration breath-by-breath. A subject wore a half-mask, inhaling gas from the conditioning chamber through the inhalation tube. The dead space of the mask was about 150 ml. A blower delivered ambient air to the chamber where CO2 was mixed if needed for a particular condition. Exhaled gas passed through the exhalation tube to the ambient air. Gas analyzers measured the amount of oxygen and CO2 in the gases in the conditioning chamber and the exhalation tube. The analyzers were calibrated with precision-analyzed gas mixtures before and after each test. A pneumotachometer measured the volume of the gas flow in the inhalation tube. The coefficient of viscosity of the inhaled air, which was needed to determine the volume precisely, was calculated from the composition of the gas and its temperature and humidity. A pressure gage measured the pressure level inside the mask. After converting from analog to digital, the signals from these devices were processed with a personal computer for the determination of ventilation (VE) and end-tidal CO2 concentration (PETCO2).

Twelve male subjects (Table 1), ranging in age from 28 to 46 yr, volunteered to participate in the tests with knowledge of the possible risks. None were aware of the purpose of the experiment. Their average height was about 170 cm and their average weight was about 68 kg. The four test conditions were breathing room air or 3% CO2 at rest or during exercise. The 3% CO2 level was
chosen on the basis of its being the permissible limit in the Japan Industrial Standard (JIS) for CCBA. The order in which room air or 3% CO₂ was administered was randomized. And throughout the test the heart rate of the subject was measured by an electrocardiograph.

A subject sat on a bicycle ergometer while breathing the test gases at room temperature (23 ± 1°C). After initial familiarization with the test conditions, data acquisition was started. The subject breathed through the mask at rest for 2 min, and started exercising by rotating the pedals at 60 rpm with a 20-W work load. After 1 min of cycling at this initial exercise load, the power output was increased every minute by 20 W until it reached approximately 40% of the maximum working capacity of the subject. The intensity of the work load of the subject while exercising was determined by the heart rate whose maximum value was evaluated from the age of the subject. This work rate was chosen as the highest intensity possible without a significant effect of lactic acid production. The subject continued the test for at least 3 min at the highest work load.

Results

Figures 2 and 3 show the ventilation rates and the end-tidal CO₂ concentrations, respectively, of one test subject. During the first 2 min at the rest condition, the values were almost stable. After starting exercise, the ventilation rate increased with the increasing intensity of the work load, and reached a stable level while steady-state exercising for the last 3 min. The ventilation rate while the subject was breathing 3% CO₂ was higher than that while breathing room air throughout the test; this was also true for end-tidal CO₂.
Table 2. Ventilation rate, end-tidal carbon dioxide concentration and slope of $\dot{V}_e$-PetCO$_2$ relationship

<table>
<thead>
<tr>
<th>Subject (W)</th>
<th>Exercise intensity</th>
<th>Rest</th>
<th>Exercise</th>
<th>Rest</th>
<th>Exercise</th>
<th>Slope (L/min/%)</th>
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<td>12</td>
<td>20</td>
<td>65</td>
<td>90</td>
<td>5.2 6.2 7.0</td>
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<tr>
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<td>12</td>
<td>21</td>
<td>47</td>
<td>68</td>
<td>5.1 6.1 7.6</td>
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<tr>
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<td>8</td>
<td>16</td>
<td>30</td>
<td>42</td>
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<td>8</td>
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<td>46</td>
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<tr>
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<td>47</td>
<td>57</td>
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<td>9</td>
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<td>16</td>
<td>38</td>
<td>43</td>
<td>4.6 6.3 5.9</td>
</tr>
</tbody>
</table>

$\dot{V}_e$: Ventilation rate; PetCO$_2$: End tidal carbon dioxide concentration; Slope, Slope of $\dot{V}_e$-PetCO$_2$ relationship; Rest, At rest; Exercise, During exercise; Air, Breathing air; CO$_2$, Breathing 3% carbon dioxide.

Figure 4 shows the relationship between the slope ($S$) at rest and during exercise for each subject. There was a close correlation between the slopes in the two conditions (CC=0.97) with the slopes during exercise about 1.7 times those at rest. Another notable characteristic of the ventilatory response was the large difference between test subjects in the values. During exercise, the slope of the most sensitive person to CO$_2$ was more than 10 times as high as that of the least sensitive person.

Discussion

The increase in ventilation rate causes severe stress in the human body, especially if the person is using a respiratory protective device with breathing resistance,
since it produces higher pressure fluctuations requiring greater energy expenditure\textsuperscript{12}. One of our concerns about the safety of using respiratory protective devices was the effect of CO\textsubscript{2} on the human body under work conditions. In order to determine the appropriate performance criteria for testing CCBA, the permissible inhaled CO\textsubscript{2} concentration should be evaluated considering CO\textsubscript{2} sensitivity during exercise. The slope of the VE-PETCO\textsubscript{2} relationship is considered to be an important practical factor indicating the human sensitivity to CO\textsubscript{2}.

Read’s rebreathing technique\textsuperscript{11} has been commonly used for measurement of ventilatory response to CO\textsubscript{2}. The advantages of this method are its simplicity and speed. Read’s method requires the subject to breathe from a 4–6 L bag which initially contains 7% CO\textsubscript{2} and 50% oxygen. But the method has been suggested to be susceptible to error during exercise, since the method is based on the assumption that there is equilibrium between the partial pressure of CO\textsubscript{2} between the rebreathing bag, alveolar, arterial blood and the tissues of the central chemoreceptors\textsuperscript{2, 13}. However, the higher oxygen consumption rate during exercise can lead to a rapid decrease in bag volume which can change the equilibrium in PCO\textsubscript{2} between the bag and the chemoreceptors\textsuperscript{2, 13}. And the high inspired CO\textsubscript{2} concentration with this method can cause an artificial change in the slope because it leads fairly quickly to a maximum ventilation rate and produces a flattening off in the CO\textsubscript{2} response curve\textsuperscript{2, 13}. Duffin\textsuperscript{11} demonstrated that during 50W exercise the maximum limits of ventilation were reached too quickly to yield an accurate response slope. So most of the research studies with the rebreathing method were limited to light exercise. Those studies found that the ventilatory response to CO\textsubscript{2} during exercise was unchanged from that at rest\textsuperscript{2-6}.

This study, using the steady-state method, found that

\[
\text{Slope of } \frac{V_E}{P_{ETCO_2}} \text{ (L/min/%)}
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\begin{figure}[h]
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\includegraphics[width=\textwidth]{fig4.png}
\caption{Individual values in $\frac{V_E}{P_{ETCO_2}}$ relationship slope at rest and during exercise}
\end{figure}

the ventilatory responses to CO\textsubscript{2} during exercise were higher than those during rest. McConnell\textsuperscript{3} and Clark\textsuperscript{4} also used the steady-state method to measure CO\textsubscript{2} response during exercise, and have reported an increase in responsiveness compared to rest conditions. Most of the work rates in these studies were moderate. But McConnell also compared the results of the steady-state method in rest and light exercise, and found the same tendency as in moderate exercise. So it is difficult to attribute the discrepancy between the results for the two methods to the difference in given work loads. Although, at the present time, we cannot determine the reason for the discrepancies, we believe that the steady-state method is the correct one to use in order to evaluate the appropriateness of the permissible inhaled CO\textsubscript{2} level for CCBA. And the reasons are based on the fact that the work rate in the present study was moderate and that the inhaled CO\textsubscript{2} concentration of the test was 3%. Moderate work loads are assumed to be common in practical use of the apparatus\textsuperscript{13, 16}, and 3% CO\textsubscript{2} is the same as the present permissible limit for inhaled CO\textsubscript{2} in JIS\textsuperscript{17}.

Under work conditions the effect of increased inhaled CO\textsubscript{2} on ventilation is stronger than that at rest. The slopes of the $\frac{V_E}{P_{ETCO_2}}$ relationship have been demonstrated to be about 70% greater in moderate exercise than at rest. So, for reasons of safety in the use of CCBA, which tends to be used under work conditions, the permissible limit for inhaled CO\textsubscript{2} of 3% is not appropriate. A minimal concentration is certainly desirable, but technical difficulties may prevent the achievement of a CO\textsubscript{2} level as low as 1%. We therefore recommend an inhaled CO\textsubscript{2} limit of 2% which we believe is achievable with present technology.

We must also consider the wide range of individual sensitivity. Among the 12 test subjects in this study, the ventilatory response of the most sensitive subject was more than ten times that of the least sensitive. This wide range in individual CO\textsubscript{2} response has been demonstrated in previous studies conducted at rest. McGurk\textsuperscript{10} reviewed the previous studies of ventilatory response to CO\textsubscript{2} and found that the highest CO\textsubscript{2} sensitivity was about 20 times as high as the lowest. We can assume the same range in sensitivity under work conditions, because the present study showed a close correlation between sensitivity at rest and at work. For safety reasons, in rescue or fire fighting activities, a person with a high ventilatory response to CO\textsubscript{2} must be excluded from CCBA use. Increase in inhaled CO\textsubscript{2} in an apparatus can increase the ventilation rate of a highly sensitive person to the extent that the severe stress might cause a dangerous situation. The rebreathing method can be used to identify those persons because of the close correlation between the ventilatory response to CO\textsubscript{2} at rest and during exercise. This is fortunate because the conventional rebreathing method is more easily performed.
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References