Re-examination of the incidence of exercise-induced hypoxaemia in highly trained subjects

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The purpose of this study was to examine the occurrence of exercise-induced hypoxaemia (EIH) during maximal exercise in highly trained athletes. Eleven trained cyclists (mean(s.d.) age 23(3.5) years; mean(s.d.) $\dot{V}O_2_{max}$ 66.9(4.8) ml kg$^{-1}$ min$^{-1}$) performed a continuous, multistage (270kpm min$^{-1}$) cycle ergometer test to exhaustion. Measurements of arterial oxygen-haemoglobin saturation (%HbO2) were obtained simultaneously at rest, every 2 min during exercise, and at maximum exercise capacity from arterial blood sampling (%SaO2) and ear oximetry (%SpO2). Exercise induced hypoxaemia (%HbO2 ≤91%) was present in 64% of the athletes examined when EIH was determined using pulse oximetry, whereas none of the subjects exhibited EIH when %HbO2 was determined using arterial blood. At rest the values for %HbO2 were similar with mean(s.d.) %SaO2 being 97.3(0.6)% and mean(s.d.) %SpO2 being 96.5(1.6)%. During exercise, statistically significant differences were found for %HbO2 between arterial blood and ear oximetry at the 6-min, 8-min, and maximal exercise sampling times (repeated measures analysis of variance, $P < 0.05$). The results indicate that ear oximetry overestimates the incidence of EIH and underestimates the oxyhaemoglobin saturation in highly trained cyclists during exercise in comparison with those measurements made from arterial blood.

Keywords: Arterial blood, desaturation, exercise, hypoxaemia, trained athletes

It has been postulated that there are two physiologic- al extremes that exist which can limit maximal exercise performance$^1$. In the untrained individual, exercise performance becomes limited due to the ‘weak links’ of the oxygen transport system and oxidative capacity of the muscular system$^{1,2}$. Whereas, in the highly trained individual, the rate limiting step becomes the anatomical and physiological constraints of the respiratory system resulting in ‘exercise-induced hypoxaemia’ (EIH)$^{1,2}$. Numerous investigations exist reporting arterial oxygen-haemo- globin desaturation in highly trained subjects during maximal exercise$^{3-10}$. When using pulse ear oximetry, it has been reported that the incidence of oxygen-haemoglobin desaturation (%HbO2 ≤ 91%) during maximal exercise occurs in approximately 50% of the highly trained athletes examined$^7$. It is interesting to note, however, that there has been no scientific study which has examined the occurrence of EIH in highly trained athletes when saturation is determined using invasive procedures (arterial blood) rather than non-invasive ear oximetry analysis. Therefore, it was the purpose of this study to examine the occurrence of arterial oxygen-haemoglobin desaturation during maximal exercise in highly trained athletes.

Materials and methods

Eleven healthy, trained cyclists of mean(s.d.) age 23.0(3.5) years served as subjects after signing an institutionally approved informed consent. Each subject had a minimum of one year’s experience as a licensed (United States Cycling Federation) competitive cyclist. Each subject reported to the laboratory 12 h after eating for data collection. Baseline ventilatory and metabolic measurements were collected following 20 min of supine rest. Subsequently, an arterial catheter (Arrow 1.25 inch, 20 Fr) was placed into either the right or left radial artery using the procedure described by Wasserman et al.$^{11}$. The ear probe for the Biox IIa oximeter (Ohmeda, Boulder, Colorado, USA) and interface cables were secured to the subject so as to minimize movement artefact as determined by laboratory experience with the instrumentation. Resting arterial blood samples and ear oximetry readings were obtained simultaneously 15 min after the catheterization procedures.

Experimental session

Each subject performed a multistage cycle ergometer aerobic capacity ($\dot{V}O_2_{max}$) test at an initial work rate of 135 W with a 45 W increase every minute until exhaustion. A ‘true’ test of $\dot{V}O_2_{max}$ was considered to be achieved if each subject met two of the following four criteria: a plateau in $\dot{V}O_2$ with increased exercise workload; a heart rate of 10% more or less than the

Table 1. General characteristics of the subjects

<table>
<thead>
<tr>
<th>Subject number</th>
<th>Age (years)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>(\dot{V}O_{2\text{max}}) (ml kg (^{-1}) min (^{-1}))</th>
<th>RER</th>
<th>Max HR (beats min (^{-1}))</th>
<th>Max VE (l min (^{-1}))</th>
<th>Lactate (mmol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28</td>
<td>179.1</td>
<td>70.0</td>
<td>-*</td>
<td>-*</td>
<td>191</td>
<td>122.0</td>
<td>9.3</td>
</tr>
<tr>
<td>2</td>
<td>18</td>
<td>177.8</td>
<td>80.5</td>
<td>65.5</td>
<td>1.20</td>
<td>189</td>
<td>190.6</td>
<td>10.3</td>
</tr>
<tr>
<td>3</td>
<td>28</td>
<td>182.9</td>
<td>86.4</td>
<td>62.4</td>
<td>1.12</td>
<td>194</td>
<td>176.4</td>
<td>8.3</td>
</tr>
<tr>
<td>4</td>
<td>23</td>
<td>182.9</td>
<td>77.3</td>
<td>72.7</td>
<td>1.13</td>
<td>184</td>
<td>210.7</td>
<td>8.5</td>
</tr>
<tr>
<td>5</td>
<td>22</td>
<td>177.8</td>
<td>75.0</td>
<td>65.7</td>
<td>1.15</td>
<td>186</td>
<td>166.0</td>
<td>9.3</td>
</tr>
<tr>
<td>6</td>
<td>22</td>
<td>191.0</td>
<td>81.8</td>
<td>68.0</td>
<td>1.24</td>
<td>188</td>
<td>199.3</td>
<td>9.2</td>
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<tr>
<td>7</td>
<td>24</td>
<td>180.3</td>
<td>84.5</td>
<td>61.9</td>
<td>1.02</td>
<td>195</td>
<td>152.5</td>
<td>12.2</td>
</tr>
<tr>
<td>8</td>
<td>20</td>
<td>190.5</td>
<td>79.5</td>
<td>74.3</td>
<td>1.16</td>
<td>181</td>
<td>150.7</td>
<td>9.7</td>
</tr>
<tr>
<td>9</td>
<td>20</td>
<td>170.2</td>
<td>56.8</td>
<td>73.4</td>
<td>1.15</td>
<td>208</td>
<td>169.3</td>
<td>9.9</td>
</tr>
<tr>
<td>10</td>
<td>19</td>
<td>180.3</td>
<td>70.5</td>
<td>66.2</td>
<td>1.26</td>
<td>192</td>
<td>134.1</td>
<td>9.5</td>
</tr>
<tr>
<td>11</td>
<td>26</td>
<td>177.8</td>
<td>81.2</td>
<td>58.9</td>
<td>1.19</td>
<td>185</td>
<td>173.2</td>
<td>6.3</td>
</tr>
</tbody>
</table>

Mean(s.d.) 22.7(3.5) 181.0(5.9) 76.7(8.4) 66.9(5.2) 1.16(0.07) 190.3(7.3) 167.7(26.9) 9.3(1.4)

*Data unavailable. RER, respiratory exchange ratio; max HR, maximum heart rate; max VE, maximum ventilation.

Age-predicted maximum; a respiratory exchange ratio greater than 1.0; and a peak whole blood lactate in excess of 8.0 mmol \(^{-1}\). As indicated in Table 1, each subject achieved a ‘true’ test of maximal aerobic capacity.

Before starting to exercise the cyclists were instructed to remain seated throughout the entire cycle exercise test to avoid extraneous movements to the ear oximeter probe. The Monark cycle ergometer (Varberg, Sweden) was modified with toe-clips, cycling seat and handle bars so as to simulate the cyclist’s typical racing bicycle. After calibration with standardized reference gases, metabolic and ventilatory data (Quinton Q-Plex, Seattle, Washington, USA) were monitored continuously throughout the cycle ergometer test, using open circuit spirometry. Oxyhaemoglobin saturations for arterial blood (%SaO\(_2\)) and ear oximetry (%SpO\(_2\)) were simultaneously obtained every 2 min throughout the cycle exercise test and at maximal exercise capacity. The arterial blood samples were stored in an ice bath and subsequently analysed within 30 min of the time of withdrawal\(^{12} \) for arterial pH, partial pressure of carbon dioxide and oxygen using a Corning 170 Blood Gas Analyzer (Ciba Corning, Medfield, Massachusetts, USA). The arterial oxygen-haemoglobin saturation was calculated automatically by the blood gas analyser. No corrections were made in blood temperature, since it has been shown that short duration, high-intensity exercise produces a minimal increase in core temperature (approximately 0.5°C)\(^{13,14} \) with these temperature changes having an insignificant effect on the determination of arterial oxygen-haemoglobin saturation\(^{19} \). Calibration of the blood gas analyser was performed using precision grade reference tank gases and commercially prepared precision grade calibration buffer standards. Blood lactate concentration was determined using a Yellow Springs Lactate Analyzer (Yellow Springs, Ohio, USA) following standardized techniques for calibration.

Statistics

Analysis of variance for a repeated measures design was used to test for statistical differences, followed by post-hoc analysis (APP-STAT; Statsoft, 1986, Tulsa, Oklahoma, USA). Statistical significance was accepted at a probability of less than 0.05.

Results

When using ear oximetry, it has been reported that the incidence of oxyhaemoglobin desaturation (as defined by: %HbO\(_2\) < 91%) in highly trained athletes during maximal exercise occurs in approximately 50% of those examined\(^7 \). Applying that criterion to the results of the present study, seven of 11 subjects (64%) would be classified as having arterial oxyhaemoglobin desaturation when %HbO\(_2\) was determined using arterial blood sampling.

The %SpO\(_2\) and %SaO\(_2\) values were similar under resting conditions with the mean(s.d.) values being 96.5(1.6)% and 97.3(0.6)%, respectively. However, statistical analysis revealed that there was a significant difference in %HbO\(_2\) determinations for arterial blood and ear oximetry at 6-min, 8-min, and maximal exercise sampling times (Table 2 and Figure 1), with these differences becoming prevalent at an exercise intensity of greater than 73% \(\dot{V}O_{2\text{max}}\).

Discussion

Although previous research using pulse oximetry indicates that approximately 50% of endurance trained athletes develop EIH (%HbO\(_2\) < 91%), the findings of the present study using arterial blood %SaO\(_2\) failed to find EIH in any of the endurance trained athletes examined. However, when using pulse ear oximetry, 64% of the athletes examined exhibited EIH. The %SaO\(_2\) responses observed in the present study are similar to the data reported by others who have investigated arterial desaturation in highly trained individuals. Dempsey et al.\(^3 \) and Hopkins and McKenzie\(^4 \), using arterial blood sampling, have shown reductions in %SaO\(_2\) from resting values of approximately 5% (%SaO\(_2\) at maximum exercise = 92%) during maximal treadmill exercise using highly trained athletes. In this study the

Table 2. Absolute and change from rest values for percentage oxygen-haemoglobin saturation during the cycle ergometer test

<table>
<thead>
<tr>
<th>Sampling time (min)</th>
<th>Oxygen uptake (% of max ( \text{VO}_2 ))</th>
<th>Ear oximeter</th>
<th>Arterial blood samples</th>
<th>Change from rest*† (%SO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rest</td>
<td>8.9</td>
<td>96.5(1.6)</td>
<td>97.3(0.6)</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>37.3</td>
<td>95.8(1.3)</td>
<td>96.7(0.8)</td>
<td>-0.6(1.6)</td>
</tr>
<tr>
<td>4</td>
<td>57.1</td>
<td>94.9(1.6)</td>
<td>96.2(1.6)</td>
<td>-1.6(2.3)</td>
</tr>
<tr>
<td>6</td>
<td>73.4</td>
<td>93.6(2.2)‡</td>
<td>95.9(1.5)</td>
<td>-2.8(3.0)</td>
</tr>
<tr>
<td>8</td>
<td>89.8</td>
<td>92.8(2.2)‡</td>
<td>95.6(1.5)</td>
<td>-3.5(3.3)</td>
</tr>
<tr>
<td>Maximal exercise</td>
<td>99.6</td>
<td>89.9(2.0)‡</td>
<td>95.0(1.7)</td>
<td>-6.6(2.9)</td>
</tr>
</tbody>
</table>

*Values are means(d.o.); †Exercise %SO₂ minus resting %SO₂; ‡Statistically different (P < 0.05)

%SaO₂ decreased by 2.3%, from 97.3% at rest to 95.0% during maximal exercise. However, it is interesting to note that none of the studies in the scientific literature that have examined invasively determined arterial blood desaturation in highly trained subjects has found %SaO₂ reductions near the magnitude recorded by non-invasive ear oximetry. Oxygen-haemoglobin saturation determined from ear oximetry (%SpO₂) will typically decrease 8–10% from rest, with the %SpO₂ values ranging between 84% and 91%. Similar changes were observed in the present study with the %SpO₂ at maximal exercise being decreased by approximately 7% from resting conditions.

Previous investigations have shown that the use of ear oximetry is valid and reliable for determining %HbO₂ in subjects who are pulmonary patients, smokers, and ‘normal’, ‘healthy’ individuals, at rest, under normoxic and hypoxic conditions. A study by Martin et al. found that pulse, ear and finger oximeters are valid at monitoring arterial oxygen-haemoglobin saturations in highly trained athletes during exercise. Yet, in that study, data were presented as the mean difference between %SpO₂ and %HbO₂ (i.e. bias) rather than actual oxygen-haemoglobin saturation, therefore it is not possible to relate those findings to the incidence of EIH in highly trained athletes. Additionally, the pulse oximeter used in the validation study by Martin et al. was the newest model pulse ear oximeter, whereas, an older model ear oximeter was used in the original study which showed the incidence of desaturation to be approximately 50% of the subjects examined.

The reason for the significant differences in oxygen-haemoglobin saturation determinations between ear oximetry and arterial blood at the higher exercise intensities is not known, however, there are a number of possible explanations for the observed differences. It has been speculated that a reduction in ear perfusion during exercise may be a factor in the difference. Although the Biox IIa is equipped with a low perfusion indicator there were no indications from the oximeter that a reduction in perfusion occurred during exercise in any of the subjects in the present study. However, the sensitivity of the low perfusion indicator to respond to perfusion limitations during exercise in highly trained subjects is unknown. Dempsey et al. showed that in highly trained runners during maximal exercise there is a substantial decrease in mean erythrocyte capillary transit time by comparison with ‘average’ individuals. The coupled effects of exercise perfusion alterations and an increased rate of blood flow in highly trained subjects during maximal exercise may result in an inability of the oximeter to measure oxygen-haemoglobin saturation of these subjects accurately at high power outputs. Research has indicated that the improper attachment of the oximeter ear probe contributes to the inaccuracy of estimating arterial oxygen-haemoglobin saturation.

The extent to which movement artefact contributed to the significantly reduced estimates of %HbO₂ in the ear oximeter is unknown. Even though precautions to prevent extraneous movements of the ear probe were taken as directed by the manufacturer, the exercise requirements may have interacted with the ear oximeter thereby contributing to the resulting difference.

The presence of elevated levels of carboxyhaemoglobin (HbCO) have been shown to alter the ability of oximeters to estimate the oxyhaemoglobin saturation. Likewise, calculated oxygen-haemoglobin saturations from arterial blood samples may not provide a true reflection of actual oxyhaemoglobin saturation since calculated values do not account for HbCO binding. Although HbCO levels were not measured in the present study, there was no reason to expect elevated arterial HbCO, since none of the subjects were smokers. Had an elevated HbCO been present in these subjects it would be expected that a...

consistent difference in saturation would have been present between the ear oximeter and arterial blood, irrespective of workload.

Although newer pulse oximeter technology is available, numerous scientific investigations are still being completed using the older oximeter technology.7,14,15,16 Given the lack of scientific validation studies for the use of older oximeters in exercising highly trained athletes and the significant differences observed for %HbO2 between non-invasive and invasive methods described in the present study, it would appear that validation of ear oximetry for determining arterial oxygen-haemoglobin saturation in highly trained individuals is strongly warranted. Co-oximeter analysis of arterial blood, which provides a detailed analysis of total haemoglobin and its subfractions (oxyhaemoglobin, methaemoglobin and carboxyhaemoglobin), would be appropriate to ensure the accuracy of reporting the incidence of oxyhaemoglobin desaturation in highly trained athletes during maximal exercise.

This study found that ear oximetry overestimates the incidence of EIH and underestimates the oxyhaemoglobin saturation in highly trained cyclists during exercise in comparison to those measurements made from arterial blood. Although ear oximetry can provide qualitative analysis for arterial blood oxygenation, the validity and accuracy of this technology used with highly trained individuals during maximal exercise remains in question and requires further examination.

Acknowledgements

Work was done at the Coal Miner’s Respiratory Disease Clinic/Cardiopulmonary Laboratory of Herrin Hospital, Herrin, Illinois, USA.

The authors would like to thank Deb Van Tassel and Regina Minton for their technical support in the collection of data for this study. Additional thanks are given to the administration, specifically Joe Hutchcraft, and the staff of the Cardiopulmonary Laboratory and the Respiratory Therapy Department of the Herrin Hospital for their support throughout this project. The authors would also like to extend a note of thanks to Dr John T. Mouw for his assistance in the statistical design for this study.

References