Maximal Fat Oxidation Rate and Cross-Over Point with Respect to Lactate Thresholds do not Have Good Agreement

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Key words
- stoichiometric equations
- carbohydrates oxidation rate
- fat oxidation rate
- cross-over concept

Abstract

The present cross-sectional study was designed to assess the agreement between maximal fat oxidation rate \( \text{maxFAT}_{OXR} \) vs. Lactate Threshold (LT), and cross-over point \( \text{CO}_P \) vs. Individual Anaerobic Threshold (IAT) in well-trained athletes. 2 groups of male, well-trained endurance athletes (short-distance triathletes (ST) \( n = 11 \)), and road cyclists (RC) \( n = 11 \)) performed a graded cycle ergometer test to exhaustion, with 4-min stages and 30-W increments. LT, IAT, \( \text{maxFAT} \), and \( \text{CO}_P \) were determined for each group. \( \text{FAT}_{OXR} \) and \( \text{CHO}_{OXR} \) were estimated by means of indirect calorimetry and stoichiometric equations. The agreement between \( \text{maxFAT}_{OXR} \) vs. LT, and \( \text{CO}_P \) vs. IAT were determined using the Bland-Altman methodology. In spite of the low systematic error (bias) (high accuracy) for \( \text{CO}_P \) vs. IAT, the variable error (limits of agreement) was moderate (moderate precision). For \( \text{maxFAT}_{OXR} \) vs. LT the systematic error was moderate (moderate accuracy), and the variable error was moderate to high (moderate to low precision). In conclusion, the data obtained from this study shows that \( \text{maxFAT}_{OXR} \) do not exhibit good agreement with LT and IAT, in male endurance well-trained athletes. Consequently, it is not possible to assume that \( \text{maxFAT}_{OXR} \) vs. LT and \( \text{CO}_P \) vs. IAT occurs at the same exercise intensity.

Introduction

Lactate thresholds (LTs) have been widely used as an indirect measure to control aerobic adaptations in endurance sports [7]. In the literature, there are numerous methods to determine LTs, some based upon the relation between blood lactate concentration \([\text{La}^-]_b\) at the final of each step during a progressive test until exhaustion and fractional \( \text{VO}_{2\max} \) \( \%\text{VO}_{2\max} \) [36]. Some authors have suggested 2 breakpoints or LTs in the exponential curve \([\text{La}^-]_b\times\%\text{VO}_{2\max} \) [35]. In general the first lactate threshold has been called \textit{Lactate Threshold} (LT) and the second one \textit{Individual Anaerobic Threshold} (IAT) [7]. 2 of the most used methodologies to determine LTs are the LT (as first LT) proposed by Davis \textit{et al.} [11] and the IAT (as second LT) proposed by Dickhuth \textit{et al.} [12]. Another methodology less widely utilised to control aerobic adaptations following exercise in endurance sports is indirect calorimetry together with stoichiometric equations to estimate fat oxidation rate \( \text{FAT}_{OXR} \) and carbohydrate oxidation rate \( \text{CHO}_{OXR} \) [23]. The relationship between \( \text{FAT}_{OXR} \) and \( \text{CHO}_{OXR} \) in relation to exercise intensity fit a parabolic and exponential equation, respectively [22]. The highest fat oxidation rate \( \text{maxFAT}_{OXR} \), in well-trained endurance athletes, occurs at moderate intensities [1,18]. Increases in exercise intensity provoke a rise of the \( \text{CHO}_{OXR} \) and a decrease of the \( \text{FAT}_{OXR} \). Patterns followed by the substrates oxidation expressed as percentage of maximum oxidation for each one of the substrates \( \%\text{FAT}_{OXR} \) and \( \%\text{CHO}_{OXR} \), in relation to whole range of aerobic exercise intensity involve the \textit{cross-over concept} hypothesized by Brooks and Mercier [8]. Moreover these authors described the \textit{cross-over point} \( (\text{CO}_P) \) as the exercise intensity at which the \( \%\text{CHO}_{OXR} \) used is higher than that of \( \%\text{FAT}_{OXR} \).

A number of investigations have been undertaken to examine the effect of exercise intensity on many variables related with the \textit{cross-over concept}. These variables have been estimated and calculated, using different protocols, by means of indirect calorimetry and stoichiometric equations in well-trained endurance athletes [1,19], healthy subjects [9,34,37,38] and obese boys [25,29]. Those variables are maximal fat oxidation rate \( \text{maxFAT}_{OXR} \), cross-over point \( (\text{CO}_P) \),...
minimal fat oxidation rate (min\(\text{FAT OXR}\)) and maximal CHO oxidation rate (max\(\text{CHO OXR}\)). A small number of these authors have focused the aim of their study to design a reproducible methodology to determine and to calculate the cross-over concept. A key question raised by Brooks and Mercier [8] was the relationship between the CO\(_2\) and the intensity related with the L Ts traditionally used for the determination of training intensities of exercise. While some authors have suggested that max\(\text{FAT OXR}\) occurs at an intensity close to the ventilatory threshold (VT) [39] or at the same intensity of lactate increase above baseline (LIAB) [37], others have observed that it occurs at a different exercise intensity than VT [2] and LT [4,18]. Nevertheless, no studies have found in the literature which assessed the agreement of max\(\text{FAT OXR}\) and CO\(_2\) respect to L Ts in endurance athletes. Thus, the present cross-sectional study was designed to assess the agreement between the exercise intensities corresponding to max\(\text{FAT OXR}\) vs. LT, and CO\(_2\) vs. IAT in well-trained male road cyclists and short-distance triathletes, and to propose a methodology to determine and to calculate the cross-over concept by means of indirect calorimetry and stoichiometric equations.

### Methods

#### Subjects

2 groups of well-trained male endurance athletes (road cyclists (n =11) (RC), and short-distance triathletes (n =11) (ST)) participated in the study. Prior to the protocol body fat was measured with the methodology proposed by Faulkner [13]. Subjects’ mean ± SD characteristics for both groups of the study are listed in **Table 1**. Testing was undertaken during the competitive phase of each individuals training cycle. Subjects were informed of the experimental protocol and provided written consent prior to enrolment. This study was conducted according to the Helsinki Statement (last modified in 2004) and has been approved by the local ethics committee, in accordance with the ethical standards of the IJSM [20].

#### Study Protocol

Prior to the trial, the athletes followed a high-CHO diet (~75% CHO, high glycemic index). Subjects were instructed on how to use household measures to record their food intake, a nutritionist advised the subjects and reviewed the completed food intake forms. Prior to the trial, the athletes followed a high-CHO diet (~75% CHO, high glycemic index). Subjects were instructed on how to record their food intake, a nutritionist advised the subjects and reviewed the completed food intake forms.

### Table 1 Characteristics of both groups of study (mean ± SD).

<table>
<thead>
<tr>
<th>RC (n = 11)</th>
<th>ST (n = 11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>age (yr)</td>
<td>21 ± 5</td>
</tr>
<tr>
<td>competitive experience (yr)</td>
<td>5.5 ± 1.3</td>
</tr>
<tr>
<td>height (cm)</td>
<td>177 ± 7</td>
</tr>
<tr>
<td>weight (kg)</td>
<td>67.2 ± 5.8</td>
</tr>
<tr>
<td>BMI (kg · m(^{-2}))</td>
<td>21.9 ± 1.3</td>
</tr>
<tr>
<td>fat (%)</td>
<td>10.1 ± 0.7</td>
</tr>
<tr>
<td>fat (kg)</td>
<td>6.8 ± 0.8</td>
</tr>
<tr>
<td>VO(_{2\max}) (mL · kg(^{-1}) · min(^{-1}))</td>
<td>64.3 ± 5.4</td>
</tr>
<tr>
<td>PPO (W)</td>
<td>355 ± 34</td>
</tr>
<tr>
<td>PPO (W · kg(^{-1}))</td>
<td>5.3 ± 0.5</td>
</tr>
</tbody>
</table>

RC: Road cyclists group; ST: Short-distance triathletes group; BMI: Body Mass Index; Fat: body fat; VO\(_{2\max}\): Maximal oxygen consumption; PPO: Peak Power Output.

#### Cross-over concept and cross-over point determination

FAT\(_{OXR}\) and CHO\(_{OXR}\) were estimated by means of Frayn’s stoichiometric equations [15], and expressed in g · min\(^{-1}\), using the average values of VO\(_2\) and VCO\(_2\) of the final 2 min of each stage measured during the cyclergometer test. It was assumed that the excretion of nitrogen in urine was negligible. Moreover, energy expenditure from FAT\(_{OXR}\) (EE\(_{FAT}\)) and CHO\(_{OXR}\) (EE\(_{CHO}\)) was estimated using the caloric equivalents from glucose [14] and from fatty acids [31], and expressed in kcal · min\(^{-1}\). Individual curves of the FAT\(_{OXR}\) vs. absolute (W) and relative (%VO\(_{2\max}\)) exercise intensities for each of the subjects were constructed by fitting the experimental data to a parabolic equation (\(y = ax^2 + bx + c\)). The values of the max\(\text{FAT OXR}\) (g · min\(^{-1}\)) and the FAT\(_{OXR}\) at 5%, 10%, and 20% of max\(\text{FAT OXR}\) were calculated with this function. An

### Capillary blood lactate and lactic thresholds determination

During the last 15 s of each stage of the laboratory test, as well as at the third minute after the end of the effort, the blood lactate concentration ([La\(_b\)]) was measured. This final register was considered as the maximal blood lactate concentration ([La\(_{b\max}\)]. Mixed arteriovenous capillary blood samples were obtained from a small incision made to the left earlobe. The incision was made using a sterile stainless steel blood lancet (Maersk Medical, Ltd., Sheffield, UK) after pre-cleansing with a pre-injection swab (Seton Healthcare Group, Oldham, UK). The first drop of blood was discarded, then 5 µL collected and measured by means of a portable lactate analyzer (Lactate Pro\(^6\), Arkay, Japan). The analyzer was calibrated prior to each test using the manufacturer’s recommendations. Once the cyclergometer test had finished, the evolution of [La\(_b\)] with respect to the developed mechanical power output was adjusted by a second-order polynomial equation, which permitted the determination of the IAT and the LT for each of the subjects. The LT was calculated according to the criteria established by Davis et al. [11] (highest exercise intensity before onset blood lactate concentration) and the IAT according to the criteria established by Dickhuth et al. [12] (exercise intensity at a lactate concentration of 1.5 mM above the one corresponding to LT).

#### Gas exchange variables

Subjects breathed through a mouthpiece attached to an integrated system of indirect calorimetry (Quark FFT\(^8\), Cosmed, Italy). Expired gas was passed through a flowmeter, an O\(_2\) analyzer, and a CO\(_2\) analyzer which were calibrated before testing using a 3-liter Hans-Rudolph syringe and gases of known concentration (4.00% CO\(_2\) and 16.00% O\(_2\)). The flowmeter and gas analyzers were connected to a computer that calculated the ventilatory frequency (VF), the tidal volume (V\(_T\)), the fraction of O\(_2\) (F\(_{O2}\)) and CO\(_2\) (F\(_{CO2}\)) exhaled; the ventilatory exchange ratio (RER), the oxygen consumption (VO\(_2\)) and the carbon dioxide production (VCO\(_2\)) were measured in real time, breath by breath, throughout the test from conventional equations [24]. The maximal oxygen uptake (VO\(_{2\max}\)) was determined as the mean value of the VO\(_2\) of the last 30 s of effort, when at least 2 of the criteria recommended by the BASES [3] were fulfilled.
average curve was obtained by plotting the average of all the subjects’ values at the previously mentioned specific points [1]. The same procedure was applied to obtain an average curve for CHOXOXR, calculating now the values of the CHOXOXR (g·min⁻¹) at the same exercise intensities, expressed as W and %VO₂max, at which the fat oxidation rate had been calculated on the previous curve. For this variable, an exponential equation (y = me^(bx)) was used [22]. To calculate the cross-over concept the oxidation rate of each one of the functions was then expressed as percentages of the corresponding maximal oxidation value (%FATOXR and %CHOXOXR), in relation to exercise intensity expressed as W and %VO₂max. The COp was determined as the point at which both functions, expressed in this new way, equalled. The most important concepts calculated by means of the cross-over concept were maxFATOXR, COp, minFATOXR and maxCHOXOXR. These methodologies were applied for each one of the study groups.

Statistical analysis
All data were reported as mean ± SD unless otherwise specified. To assess the agreement between maxFATOXR vs. LT and between COp vs. IAT for each group of study, expressed in absolute (W) and relative (%VO₂max) terms, the Bland-Altman methodology was used [5]. Despite the values fitting normal distributions, a significant relation between the studied variables was not found except of the relation COp vs. IAT of RC group expressed as W (Table 3). When Kendall’s tau did not show a significant relation (data homocedasticity) the standard deviation of the differences did not depend on the magnitude of the independent variable (Fig. 3, 4a–c). In the case that Kendall’s tau showed a significant relation (data heteroscedasticity) a logarithmic transformation of the data was performed. However, this statistical procedure did not eliminate

Results
The influence of exercise intensity for whole range of aerobic intensities studied (30–100 %VO₂max) on FATOXR, CHOXOXR, EEFAT and EECHO for each group can be observed in Fig. 1. Moreover, the cross-over concept together with the curve [La⁻]ₕ-%VO₂max for each group are shown in Fig. 2. Furthermore, Table 2 shows mechanical, cardiac and metabolic values corresponding to the exercise intensities for maxFATOXR, LT, IAT, and COp in both study groups.

Once the differences between maxFATOXR vs. LT, and COp vs. IAT expressed in absolute (W) and relative (%VO₂max) terms had been plotted against the mean values for each group of study, Kendall’s tau correlation coefficient was calculated. Despite the values fitting normal distributions, a significant relation between the studied variables was not found except of the relation COp vs. IAT of RC group expressed as W (Table 3). When Kendall’s tau did not show a significant relation (data homocedasticity) the standard deviation of the differences did not depend on the magnitude of the independent variable (Fig. 3, 4a–c). In the case that Kendall’s tau showed a significant relation (data heteroscedasticity) a logarithmic transformation of the data was performed. However, this statistical procedure did not eliminate
Consequently, in this case the standard deviation of the diﬀerences was little (2.6% ± 0.01), even if absolute residuals showed normal distributions. The method described by Bland and Altman [5] showed a moderate systematic error (bias) either expressed in relative (14.9%±VO2max) or absolute (46 W) intensity, nevertheless, the variable error was broad (±32.0%±VO2max, or ±147 W). Regarding the agreement between CO2 vs. IAT (© Fig. 4c, d), the bias was near to zero (−0.6% and −6 W), although the variable error was wide (±18.3%, or ±72 W). In the group RC, the agreement between the maxFATOXR vs. LT (© Fig. 4a, b) showed a moderate systematic error expressed as relative (14.9%±VO2max) and absolute (46 W) intensity, whereas the variable error was broad (±32.0%±VO2max, or ±147 W). According to the agreement between CO2 vs. IAT (© Fig. 4c, d), the variable error expressed as % VO2max was little (2.6%) and wider when it was expressed in W, fluctuating between 41 and −21 W. The variable error was wide expressed as % VO2max (±14.8%) as well as W (Upper limit between 109 to −26 W, and lower limit between −28 to −18 W).

### Table 2

Values corresponding to the exercise intensities of maxFatOXR, LT, IAT, and CO2 of both groups of study (mean ± SD).

<table>
<thead>
<tr>
<th>VO2max (%)</th>
<th>PO (W)</th>
<th>HR (ppm)</th>
<th>[La]b (mM)</th>
<th>VO2 (mL · kg⁻¹ · min⁻¹)</th>
<th>VO2 (L · min⁻¹)</th>
<th>FATOXR (g · min⁻¹)</th>
<th>CHO2OXR (g · min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC (n = 11)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>maxFatOXR</td>
<td>52.3 ± 7.2</td>
<td>185 ± 30</td>
<td>131 ± 13</td>
<td>1.17 ± 0.19</td>
<td>35.7 ± 7.0</td>
<td>2.4 ± 0.4</td>
<td>0.45 ± 0.14</td>
</tr>
<tr>
<td>LT</td>
<td>67.3 ± 5.0</td>
<td>240 ± 53</td>
<td>149 ± 17</td>
<td>1.49 ± 0.27</td>
<td>44.9 ± 9.8</td>
<td>3.0 ± 0.7</td>
<td>0.39 ± 0.19</td>
</tr>
<tr>
<td>IAT</td>
<td>77.4 ± 4.4</td>
<td>274 ± 30</td>
<td>162 ± 8</td>
<td>2.53 ± 0.17</td>
<td>51.3 ± 5.4</td>
<td>3.5 ± 0.3</td>
<td>0.23 ± 0.18</td>
</tr>
<tr>
<td>CO2</td>
<td>74.8 ± 7.6</td>
<td>266 ± 44</td>
<td>158 ± 13</td>
<td>2.47 ± 1.06</td>
<td>49.9 ± 7.9</td>
<td>3.4 ± 0.5</td>
<td>0.26 ± 0.10</td>
</tr>
<tr>
<td>minFatOXR</td>
<td>87.3 ± 8.7</td>
<td>312 ± 51</td>
<td>174 ± 14</td>
<td>4.62 ± 2.03</td>
<td>56.8 ± 8.0</td>
<td>3.8 ± 0.5</td>
<td>0.00 ± 0.00</td>
</tr>
<tr>
<td>maxCHO2OXR</td>
<td>100 ± 0</td>
<td>355 ± 34</td>
<td>190 ± 7</td>
<td>8.14 ± 1.79</td>
<td>64.7 ± 5.5</td>
<td>4.3 ± 0.3</td>
<td>0.00 ± 0.00</td>
</tr>
<tr>
<td>ST (n = 11)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>maxFatOXR</td>
<td>52.0 ± 5.7</td>
<td>185 ± 20</td>
<td>131 ± 17</td>
<td>1.91 ± 0.75</td>
<td>32.9 ± 5.1</td>
<td>2.3 ± 0.4</td>
<td>0.39 ± 0.11</td>
</tr>
<tr>
<td>LT</td>
<td>63.7 ± 5.8</td>
<td>227 ± 51</td>
<td>143 ± 13</td>
<td>2.08 ± 0.62</td>
<td>39.6 ± 3.5</td>
<td>2.8 ± 0.3</td>
<td>0.34 ± 0.11</td>
</tr>
<tr>
<td>IAT</td>
<td>74.1 ± 8.6</td>
<td>264 ± 31</td>
<td>153 ± 14</td>
<td>3.33 ± 0.73</td>
<td>45.4 ± 4.6</td>
<td>3.2 ± 0.4</td>
<td>0.22 ± 0.17</td>
</tr>
<tr>
<td>CO2</td>
<td>74.6 ± 6.1</td>
<td>267 ± 33</td>
<td>154 ± 15</td>
<td>3.55 ± 1.59</td>
<td>45.9 ± 6.3</td>
<td>3.3 ± 0.5</td>
<td>0.21 ± 0.08</td>
</tr>
<tr>
<td>minFatOXR</td>
<td>86.2 ± 6.1</td>
<td>310 ± 44</td>
<td>165 ± 14</td>
<td>5.50 ± 2.27</td>
<td>50.7 ± 5.5</td>
<td>3.6 ± 0.5</td>
<td>0.00 ± 0.00</td>
</tr>
<tr>
<td>maxCHO2OXR</td>
<td>100 ± 0</td>
<td>358 ± 36</td>
<td>180 ± 11</td>
<td>8.93 ± 2.47</td>
<td>58.7 ± 4.8</td>
<td>4.2 ± 0.4</td>
<td>0.00 ± 0.00</td>
</tr>
</tbody>
</table>

### Table 3

Kendall’s tau correlation coefficients of the diﬀerences vs. average values between maxFatOXR vs. LT and CO2 vs. IAT.

<table>
<thead>
<tr>
<th></th>
<th>VO2max (%)</th>
<th>RC</th>
<th>p</th>
<th>ST</th>
<th>r</th>
<th>p</th>
<th>P (W)</th>
<th>RC</th>
<th>p</th>
<th>ST</th>
<th>r</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>maxFatOXR vs. LT</td>
<td>−0.094</td>
<td>0.694</td>
<td>0.241</td>
<td>0.309</td>
<td>−0.277</td>
<td>0.291</td>
<td>0.315</td>
<td>0.223</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO2 vs. IAT</td>
<td>0.110</td>
<td>0.639</td>
<td>−0.130</td>
<td>0.584</td>
<td>0.709</td>
<td>0.002</td>
<td>0.257</td>
<td>0.274</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

© Fig. 3c, d the bias was near to zero (−0.6%, and −6 W), although the variable error was wide (±18.3%, or ±72 W). In the group RC, the agreement between the maxFATOXR vs. LT (© Fig. 4a, b) showed a moderate systematic error expressed as relative (14.9%±VO2max) and absolute (46 W) intensity, nevertheless, the variable error was broad (±32.0%±VO2max, or ±147 W). Regarding to the agreement between CO2 vs. IAT (© Fig. 4c, d), the variable error expressed as % VO2max was little (2.6%) and wider when it was expressed in W, fluctuating between 41 and −21 W. The variable error was wide expressed as % VO2max (±14.8%) as well as W (Upper limit between 109 to −26 W, and lower limit between −28 to −18 W).
Discussion

The results of the present study agree with those reported by previous studies in which it has been shown that exercise intensity is one of the main factors that determine the \( \text{FAT}_{\text{OXR}} \) and \( \text{CHO}_{\text{OXR}} \) patterns, measured by different methodologies [2,8,22,38].

To understand the agreement between the parameters studied, it is important to take account of the measurement error of the instruments. It has been demonstrated previously that the Lactate Pro\textsuperscript{®} analyzer has good agreement with respect to enzymatic systems of reference [32]. Best agreement was found in the range 0.8–6 mM [28], precisely this range where LT (1.22–1.76 mM) and IAT (2.36–4.06 mM) were determined in this study.
study. However, the recalculated agreement from the study’s data of McLean et al. [28] for that range was 0.05 ± 1.06 mM. These errors expressed in %VO₂max at LT corresponded to 0.7 ± 10.9% for ST and 0.6 ± 9.7% for RC, and at IAT corresponded to 0.4 ± 8.6% for ST and 0.4 ± 8.3% for RC. Secondly, indirect calorimetry has an established accuracy of 3.0%. This systematic error at maxFAT_OXR corresponded to 1.7 %VO₂max for ST and 1.9 %VO₂max for RC, and at CO₂ corresponded to 2.3 for ST and 2.4 %VO₂max for RC. Finally, it has been suggested that stoiquimetric equations are reliable with respect to breath ¹³C/¹²C ratio method [33]. The agreement from the study’s data is −0.07 ± 0.53 g · min⁻¹ for CHO_OXR and 0.00 ± 0.16 g · min⁻¹ for FAT_OXR for intensities of 80–85 %VO₂max. However, these estimates of error cannot be applied to the present study because maxFAT_OXR (45.1–59.5 %VO₂max) was measured under these intensities, and the main part of CO₂ (65.5–82.7 %VO₂max), too. Although the measurement error of the instruments was known, regarding the agreement between maxFAT_OXR vs. LT (Fig. 3, 4), it was not possible to entirely explain both the systematic error (bias) and variable error (limits of agreement) for each study group. The remaining error without explanation for ST was 9.3 ± 1.0 %VO₂max, and for RC 12.4 ± 2.3 %VO₂max. Although, with respect to the agreement between CO₂ vs. IAT (Fig. 3, 4), it was possible to explain all systematic errors (bias) due to instrument’s measurement error, but not the whole variable error (limits of agreement). In this sense, the remaining variable error for ST was ±9.7 %VO₂max, and for RC ±6.5 %VO₂max. Consequently, the remaining instrument’s error either for maxFAT_OXR vs. LT or CO₂ vs. IAT was due to other non-controlled disturbing variables [21] which could include, for example, the error from stoiquimetric equations. In the present study good agreement (high accuracy and moderate precision) of these equations has been determined regarding intensities of 80–85 %VO₂max [33]. It is not possible to estimate accurately the error for the whole range of aerobic intensities measured. This error is based on the non-metabolic CO₂ that come from body CO₂ stores measured at the mouth, especially from bicarbonate plasma stores [30]. This overmeasured CO₂ would affect the estimation of FAT_OXR and CHO_OXR through the stoiquimetric equations. To be more precise, for each 1 mM reduction in plasma, bicarbonate concentration of −0.41 of CO₂ is released [27].

Definitively, the agreement for CO₂ vs. IAT was moderate (low systematic error or high accuracy, and moderate variable error or precision), and the agreement for maxFAT_OXR vs. LT was moderate to low (moderate systematic error or accuracy, and moderate to high variable error or moderate to low precision). In spite of a large part of the error of measurement being potentially explained by the instruments’ measurement error, from a clinical perspective, it was not possible to assume errors over 10 %VO₂max that correspond to around 35 W in the present study. The reason is that between LT and IAT, in this study, a difference around 10 %VO₂max exists, and it is assumed that this amount of error would mean that it should not possibly discriminate the LTs. Other authors, however, have assumed higher variable errors to accept a good agreement comparing electromyographyc thresholds (EMG₁ and EMG₂) in respect to ventilatory thresholds (VT₁ and VT₂) and LTs (LT and OBLA) in professional cyclists [26]. Thus, in the present study, maxFAT_OXR and CO₂ good agreement was not found with LT and IAT, expressed either in relative (%VO₂max) terms or in absolute terms (W). Whilst studies exist that have applied similar methodologies to study the FAT_OXR in well-trained athletes [1, 18, 37], it is thought that the present study is the first to study the agreement between CO₂ with respect to another threshold. The moderate bias of maxFAT_OXR vs. LT, in the present study, agrees with other authors who found significant differences between maxFAT_OXR and LT [18] in well-trained endurance athletes. A study that investigated the agreement between maxFAT_OXR in regard to lactate increase above baseline (LIAB), a similar concept than LT, was the study of Tolfrey et al. [37]. The results of the present study did not agree with those of these authors, who suggested that a good agreement existed between maxFAT_OXR vs. LIAB, because 14 from 24 female and male adolescents that they studied were within the tolerance limit given by the minimum important difference of ±8 %VO₂max (−3.8 ± 8.0 %VO₂max).

Whilst indirect calorimetry together with stoiquimetric equations have been used in some studies to estimate and calculate, with different protocols, the cross-over concept in healthy subjects [38] and obese people [6, 29], original articles that had applied similar methodologies to determine the cross-over concept in athletes were not found. Some limited communications have been made at international congresses by the author describing the cross-over concept and determining the cross-over point in elite triathletes, elite and Pro Tour professional road cyclists [17, 19] and also in a group of junior elite soccer players [16].

One of the most important contributions of the present study is the proposal of a specific design to estimate and calculate the cross-over concept as well as the variables associated with it (maxFAT_OXR, CO₂, minFAT_OXR, and maxCHO_OXR). This specific methodology proposed to study the cross-over concept for the whole range of aerobic intensities (from 30 to 100 %VO₂max) by means of indirect calorimetry and stoiquimetric equations. For that reason it is a potentially useful tool for the orientation of training programs and for assessing the adaptations in medium-endurance and long-endurance sport specialities. Understanding the needs of FAT_OXR and CHO_OXR during competition and assessing muscular oxidation adaptations due to training with the aim of enhancing an athlete’s ability to oxidise fats and economise the use of glycogen, thus improving performance [10].

In conclusion, the data obtained from this study shows that, in male well-trained endurance athletes, the maxFAT_OXR and CO₂ occur at different exercise intensities than the proposed concepts of LT and IAT, respectively. Variables related with the cross-over concept (maxFAT_OXR, CO₂, minFAT_OXR, and maxCHO_OXR) open a new perspective for the assessment of the aerobic adaptation for athletes of medium and long duration endurance modalities. Further longitudinal studies are required to evaluate the effects of aerobic training on the cross-over concept and to assess the adaptations on the FAT_OXR and CHO_OXR. However, further study is required to investigate the validity of stoiquimetric equations for the whole range of aerobic intensities of exercise to elucidate a reference methodology for the estimation of FAT_OXR and CHO_OXR.

Acknowledgements

The author would like to express his gratitude to the participating athletes for their cooperation. Financial support for this study was received from the Spanish Ministry of Science and Innovation. DEP2008-03204.
References


