# Validation of breath-by-breath measurements of oxygen consumption using the Oxycon Pro analyzer

## I. BACKGROUND AND AIM

The rate of oxygen consumption at the mouth can be measured breath-by-breath by continuously monitoring the flow and composition of exhaled and inhaled gases. This requires time-aligned gas and flow measurements, which can be challenging due to the gas sample's transit time from the mouth to the analyzer. This time-alignment is not required using the Douglas bag or mixing chamber methods because only the volume and contents of exhaled gas are measured. However, these methods are incapable of instantaneous (i.e. breath-by-breath) measurements of $\dot{V}O_2$. For the purposes of the current study, instantaneous measurement of $\dot{V}O_2$ was a key point because of the rapidly changing exercise intensity.

The validity of the oxygen analyzer (Oxycon Pro, Erich Jaeger GmbH, Hoechberg, Germany) we used in the current study has previously been assessed by Rietjens et al. [1]. They concluded that there were no systematic differences between the Oxycon Pro in breath-by-breath mode and the Douglas bag method for measurements of $\dot{V}O_2$. However, this conclusion was based on statistical methods that were later questioned[2] (Note 13). Consequently, the aim of the experiment presented here was to re-assess the validity of breath-by-breath measurements of oxygen consumption using the Oxycon Pro analyzer. As a criterion measurement the Oxycon Pro was used in mixing chamber mode. This measurement mode has previously been shown to be valid against the Douglas bag method[3].

## II. METHODS

Six participants were recruited amongst employees and students at the Norwegian School of Sport Sciences. All participants completed 3 sub-maximal loads à 5 minutes of treadmill running ($N = 2$) or ergometer cycling ($N = 4$). The loads were 8.0, 9.0, 10.0 km·h$^{-1}$ at 6° for treadmill running or 150, 200 , 250 W for cycling. After a 3 minute recovery period, the volunteers completed an incremental test to exhaustion to determine $\dot{V}O_{2,\mathrm{peak}}$. During this test exercise intensity was increased every minute in increments of 1 km·h$^{-1}$ or 25 W for running or cycling, respectively. The protocol was repeated on two different test days; one with the Oxycon Pro in breath-by-breath mode, the other in mixing chamber mode. The order of the two test days was randomized. $\dot{V}O_2$ measured during the last 2 minutes of the sub-maximal loads and the last minute during the $\dot{V}O_{2,\mathrm{peak}}$ protocol were included in the analysis, leading to 24 pairs of $\dot{V}O_2$ measurements.

The validity of the breath-by-breath measurements was assessed through the calibration equation

$$\dot{V}O_2{}^{\mathrm{mix}} = \beta_0 + \beta_1 \cdot \dot{V}O_2{}^{\mathrm{b\times b}}, \quad (1)$$

following the recommendations of Hopkins et al. [2]. In Equation 1, $\dot{V}O_2{}^{\mathrm{mix}}$ and $\dot{V}O_2{}^{\mathrm{b\times b}}$ are measurements using mixing chamber mode and breath-by-breath mode, respectively, and $\boldsymbol{\beta} = [\beta_0, \beta_1]$ was determined from ordinary least squares regression. $\beta_1$ represents a proportional bias and $\beta_0$ an additive bias. The regression coefficients were tested against the null hypothesis $\boldsymbol{\beta} = [0, 1]$ using two single sample t-tests without correction for multiple comparisons. The standard error of the estimate of the model in Equation 1 was used to assess measurement precision.

## III. RESULTS

The calibration equation's coefficients were $\beta_0 = -0.14 \pm 0.08$ L·min$^{-1}$ ($p = 0.05$) and $\beta_1 = 1.10 \pm 0.02$ ($p < 0.0001$). This implies a trivial additive bias, but a significant proportional bias which leads to an underestimation of $\dot{V}O_2$ by about 9 % in breath-by-breath mode compared to mixing-chamber mode. The standard error of the estimate was 0.11 L·min$^{-1}$ and the coefficient of determination $R^2 = 0.99$. The results of all loads are shown in the scatter plot in Figure 1.

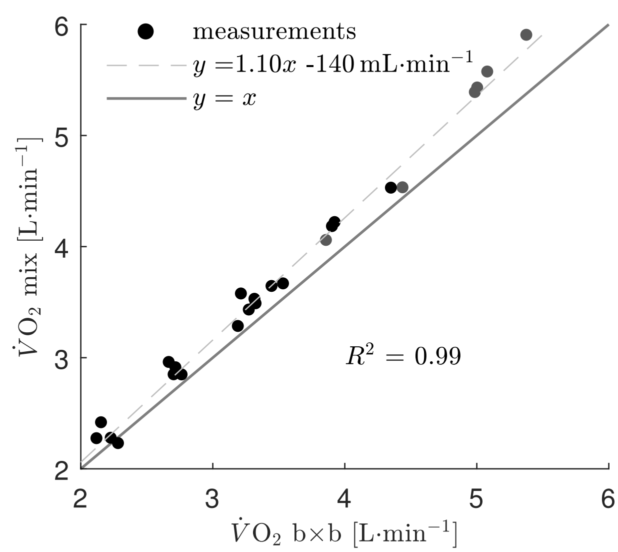


Fig. 1 Results from validation of $\dot{V}O_2$ measured using breath-by-breath mode (b×b) against mixing chamber mode (mix). Black dots are from sub-maximal loads; gray dots are from the $\dot{V}O_{2,\mathrm{peak}}$-test; dotted line is the least squares linear regression line; full line is the line of identity.

## IV. DISCUSSION AND CONCLUSION

The findings of this experiment indicate a systematic difference between measurements in mixing chamber mode and breath-by-breath mode for the Oxycon Pro analyzer. However, previous studies that validated the analyzer in mixing chamber mode[3] and breath-by-breath mode[1] both concluded that the Oxycon Pro provided valid measurements of $\dot{V}O_2$. Consequently, the results of the two aforementioned studies and those presented here appear to be in conflict.

To resolve this conflict it is important to note that Rietjens et al.[1] observed an underestimation of $\dot{V}O_2$ when $\dot{V}O_2 > 4\,\mathrm{L{\cdot}min^{-1}}$, but concluded that this observation was not statistically significant. In contrast, no such deviation was apparent when the analyzer was in mixing chamber mode[3]. Another important note is that Rietjens et al.[1] did a linear regression similar to the analysis presented in this study, although the regressor and predictor were interchanged compared to Equation 1. Rietjens et al.[1] found that

$$\dot{V}{O_2}^{\mathrm{b\times b}} = 0.31114 + 0.8896 \cdot \dot{V}{O_2}^{\mathrm{Db}}, \tag{2}$$

where $\dot{V}{O_2}^{\mathrm{Db}}$ was measured with the Douglas bag method. Coefficients comparable to $\boldsymbol{\beta}$ in this appendix can be obtained by rearranging Equation 2. This results in $\beta_0 = -0.35\,\mathrm{L{\cdot}min^{-1}}$ and $\beta_1 = 1.12$, which agrees well with the findings of this appendix. Consequently, when analyzed using alternative statistical methods, the results of Rietjens et al.[1] support the conclusion of biased $\dot{V}O_2$-measurements when the Oxycon Pro is used in breath-by-breath mode.

The method used in this appendix follows the recommendations of leading statisticians in the field[2], while the methods used in[1] did not. Moreover, when the recommended statistical methods are applied to the findings in[1] they are in agreement with the findings of this appendix. Therefore, we conclude that: (i) the Oxycon Pro underestimates $\dot{V}O_2$ when used in breath-by-breath mode; (ii) it is appropriate to apply corrections using Equation 1 to measurements done in breath-by-breath mode; (iii) after correction with Equation 1 the standard error of the estimate is $0.11\,\mathrm{L{\cdot}min^{-1}}$.

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[2] W. G. Hopkins, S. W. Marshall, A. M. Batterham, and J. Hanin. Progressive Statistics for Studies in Sports Medicine and Exercise Science. *Med. Sci. Sport. Exerc.*, 41(1):3–12, 2009. doi:10.1249/MSS.0b013e31818cb278.

[3] Ø. Foss and J. Hallén. Validity and stability of a computerized metabolic system with mixing chamber. *Int. J. Sports Med.*, 26:569–575, 2005. doi:10.1055/s-2004-821317.