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ORIGINAL PAPER

Measurement of oxygen uptake: Validation of a ''mask-free'' method

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Abstract In clinical practice, oxygen uptake is an indicator of cardiopulmonary performance. Most commercial systems measure oxygen uptake by collecting expired air through masks or mouthpieces which are often poorly tolerated by the patient. We have developed and validated a novel mask-free system to improve patient comfort and performance. The prototype is composed of a soft walled funnel that collects and conveys the expired air, together with some external air, in a mixing chamber by means of an aspiration system. Oxygen concentration and airflow are measured and then oxygen uptake is calculated. Direct comparison between calculated and preset oxygen uptake values obtained by a mechanical simulator was performed. Errors ranged between 1% and 3.3%, depending on the absolute value of oxygen consumption. Then the prototype was connected "in-series" with a breath-by-breath commercial system, and ten subjects were submitted to a standard stress test. The results showed good agreement ($R = 0.94$) and a mean difference of 5% between the peak values. The longer response time of the prototype caused a delay between the two $\dot{V}_{O_2}(t)$ curves, leading to an underestimation in the exercise phase and an overestimation in the recovery phase, suggesting more technical improvements. Nevertheless in its present form the new system can be used in the whole exercise phase and, with caution, also in the recovery phase.

Introduction

Exercise stress testing is commonly used in clinical practice to evaluate the performance of the pulmonary and cardiovascular systems [1,2]. In particular, the cardiopulmonary stress test (CPX or CPET) measures respiratory gas exchange (oxygen uptake, carbon dioxide output and minute ventilation) and monitors electrocardiogram, blood pressure and

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pulse oxymetry, typically during a symptom-limited maximal progressive exercise test.

Nowadays many commercial systems measure oxygen uptake using different technologies. They all have high performance but are also complex and expensive [1]. Most systems use masks or mouthpieces to collect expired air, resulting in patient discomfort, which may shorten the exercise tolerance and limit the diagnostic value of the test. To overcome these drawbacks, we developed a novel ''mask-free'' system to improve patient comfort and performance. At the moment this system measures only oxygen uptake but it may easily be upgraded to monitor carbon dioxide production as well.

The aim of this work was to validate the new device as a prototype, comparing its results on normal subjects with those of a mechanical pumping simulator and then with those of a commercial system.

Theoretical background

Oxygen uptake $(\dot{V}_{O_2})$ is the amount of oxygen extracted from inspired air in a given period of time and used for metabolic activity, measured in ml O_2/min or in ml/kg/min (referred to body weight) [1,2,4]. Under steady state conditions, respiratory oxygen uptake $(\dot{V}_{O_2})$ measured at the mouth corresponds to oxygen utilization in the whole body's metabolic processes, thus ''external'' respiration equals ''internal'' respiration [3,4] and depends on three major physiological functions: ventilation, oxygen transport and muscle activity [3].

With respect to ventilation (VE), oxygen uptake $\dot{V}_{O_2}$ can be described as

$$\dot{V}_{O_2} = \mathrm{VE}(\mathrm{FiO_2} - \mathrm{FeO_2}) \qquad (1)$$

where FiO_2 = inspiratory oxygen fraction [ml O_2/l air BTPS], FeO_2 = expiratory oxygen fraction [ml O_2/l air BTPS], VE = air volume exhaled from lungs in a minute [l/min BTPS] [3]. In practice the measures of patient ventilation and oxygen content in inspired and expired air are necessary and sufficient to calculate oxygen uptake.

Currently two procedures are used to measure $\dot{V}_{O_2}$ in a clinical setting: the breath-by-breath method and the mixing chamber method [1]. The breath-by-breath method measures air volume, FiO_2 and FeO_2 at the mouth for every single breath, calculates the difference between oxygen intake and outtake and gives a final $\dot{V}_{O_2}$ value by averaging the values obtained on complete breaths for a fixed time interval (10—20—30 s) [1,5]. The mixing chamber method calculates $\dot{V}_{O_2}$ by the mean flow and mean O_2 content of the air passing through a chamber in series with the patient's expiratory line [1,5]. Both systems employ mass flow sensors or pneumotachographs to measure airflow [5], and paramagnetic or electrochemical analysers [5] to measure O_2 concentrations in the expired air (the oxygen concentration of the inspired air is assumed constant). Rapid response oxygen and airflow sensors are essential in the breath-by-breath method, while slower response sensors are suitable for the mixing chamber technique [1,5]. Despite method differences, the validity of these systems relies on efficient collection of all the expired air, making masks and mouthpieces essential.

The advantage of the breath-by-breath method is a lower response time, which is mandatory in special procedures on athletes. On patients this benefit is reduced by a wide breath-to-breath variability, requiring an averaging process which increases the response time to values similar to mixing chamber solutions. Nevertheless the breath-by-breath (B $\times$ B) system is considered the best technical solution and is widely utilized to follow the oxygen uptake process with the maximal temporal resolution. The B $\times$ B system has two main limits: (1) additional errors introduced by gas volume measurement and corrections, due to the instability of temperature and aqueous vapour content at the mouth where the measurements are performed, and (2) a mandatory algorithm to compensate the delay (due to the gas sampling line) between the sampled signals of air flux and oxygen concentration [1,5].

The mixing chamber technique yields accurate measurements during steady or slowly varying exercise procedures [1,4,5]: the response time is proportional to the ratio between chamber volume and patient ventilation. The response time varies during a progressive load stress test procedure in relation to ventilation and the instantaneous results on different patients are not always readily comparable. This technique can be improved using a chamber with an internal mobile wall to vary the chamber volume and consequently the system time response. This will change the chamber volume proportionally to the subject's ventilation, yielding a ''constant time response system'' and a more stable signal throughout a progressive stress test. Again, the air flux must be corrected for temperature change and water vapour content [1,5], but the mixing process reduces the instability of the parameters, making the approach easier.

Clinical applications mainly address two parameters: the maximal oxygen uptake $\dot{V}_{O_{2max}}$ (or in absence of a plateau, $\dot{V}_{O_{2peak}}$) and the anaerobic threshold, AT [1,2,4]. $\dot{V}_{O_{2max}}$ is defined as the highest attainable O_2 uptake for a subject in a progressive load test and is used as the best index of respiratory efficiency [1,2]. The anaerobic threshold, AT, is the $\dot{V}_{O_2}$ value marking the limit point above which aerobic energy production at muscular level is supplemented by anaerobic mechanisms, causing an abnormal increase in CO_2 and lactate production. Above the AT exercise endurance is reduced [1,2,4].

The need for a face mask or mouthpiece to collect all the expired air is a major limitation for the patient, who cannot always accomplish the stress test procedure correctly. The main purpose of the present project is to eliminate the mask or mouthpiece, with an ''acceptable'' loss in precision (10%).

Materials and methods

Proposed system

The experimental system is based on evidence that, during free respiration, air is inhaled homogeneously from the space surrounding the mouth, whereas expiration breath generates a forward jet of air limited in area. Collection of the whole jet