Journal of Science and Medicine in Sport (2007) **10**, 341—350

Journal of Science and Medicine in Sport

www.elsevier.com/locate/jsams

REVIEW

Physiological consequences of a high work of breathing during heavy exercise in humans

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Received 13 February 2007; accepted 18 February 2007

KEYWORDS
Work of breathing;
Expiratory flow limitation;
Diaphragm fatigue;
Respiratory limitations

Summary The healthy respiratory system has a remarkable capacity for meeting the metabolic demands placed upon it during strenuous exercise. For example, in order to regulate alveolar partial pressure of oxygen and carbon dioxide during heavy workloads, a 20-fold increase in alveolar ventilation can occur. The high metabolic costs and subsequent increased work of breathing associated with this ventilatory increase can result in a number of limitations to the healthy respiratory system. Two examples of respiratory system limitations that are associated with a high work of breathing are expiratory flow limitation and exercise-induced diaphragmatic fatigue. Expiratory flow limitation can lead to an inability to increase alveolar ventilation ($\dot{V}_A$) in the face of increasing metabolic demands, resulting in gas exchange impairment and diminished endurance exercise performance. Furthermore, the high ventilatory requirements of endurance athletes and the inherent anatomical differences in females could make these groups more susceptible to expiratory flow limitation. Fatigue of the diaphragm has also been documented after strenuous exercise and may be related to a mechanism which increases sympathetic vasoconstrictor outflow and reduces limb blood flow during prolonged exercise. This competition between the muscles of respiration and locomotion for a limited cardiac output may have dramatic consequences for exercise performance. This brief review summarizes the literature as it pertains to the work of breathing, expiratory flow limitation, and exercise-induced diaphragmatic fatigue in healthy humans.

Contents

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doi:10.1016/j.jsams.2007.02.003

Introduction

In general, the functional capacity of the healthy human respiratory system including the lung, chest wall, and neural control systems, exceeds the demands placed upon it during heavy exercise. This is an impressive feat considering the major challenges the respiratory system must face during intense exercise. For example, the healthy respiratory system faces the major challenge of regulating alveolar partial pressure of oxygen and carbon dioxide through a considerable increase in alveolar ventilation ($\dot{V}_A$), which often exceeds resting levels by more than 20 times. This task is achieved through the capacity of the respiratory musculature for force development, and it is imperative that the physiological cost associated with such an increase in ventilation not be excessive.

The ability for the healthy respiratory system to overcome these challenges is quite remarkable but there are exceptions when the respiratory system can become limited during exercise. For example, the necessary increase in ventilation to maintain blood gas homeostasis during exercise can be compromised in some individuals resulting in a high work of breathing. When these ventilatory demands exceed the capacity for the lung and chest wall to generate flow and volume, expiratory flow limitation (EFL) can develop which may result in diaphragm fatigue. Both of these factors may potentially lead to diminished exercise performance due to a competitive relationship between respiratory and locomotor muscles for blood flow.[1,2]

The purpose of this review is to examine the current literature as it pertains to a high work of breathing during exercise and its relation to EFL and exercise-induced diaphragmatic fatigue in healthy, asymptomatic men and women. To search the available scientific literature we utilized the PubMed scientific electronic data base (www.ncbi.nlm.nih.gov./PubMed/) in addition to manual journal searches. Bibliographies of articles selected were used to find additional pertinent references. The key search phrases used included: 'work of breathing', 'expiratory flow limitation', 'diaphragm fatigue', 'ventilation', 'ventilatory constraint' 'gender', 'sex', and 'exercise'. The articles must have used healthy participants. Those studies involving participants with respiratory or cardiovascular disease or other complications were not included. Age, sex and fitness differences were not excluding factors.

Mechanical work of breathing

The work necessary to ventilate the lungs can be divided into elastic and non-elastic work components. Elastic work is composed of work that must be done against lung elastic recoil, chest wall recoil, and surface tension. The non-elastic component refers to the effort required to overcome airway resistance but includes a small contribution from tissue resistance. The work of breathing can be further subdivided into sub-components including inertial forces, gravitational forces, and distorting forces of the chest wall. The total mechanical work done during breathing is the sum of all elastic work and work against gravity done during inspiration and/or expiration, all flow resistive work except that done by previously stored elastic energy and all negative work.[3] With progressive exercise to exhaustion, the increase in minute ventilation ($\dot{V}_E$) results in a disproportionate increase in the work and O_2 cost of breathing.[4] Fig. 1 demonstrates how the work and O_2 cost of breathing increases in a similar fashion during progressive intensity exercise based on regression equations obtained in healthy and fit subjects with normal respiratory function.

Metabolic costs of a high work of breathing

As one would expect, the work of breathing will increase when $\dot{V}_E$ is increased, and therefore, the energy demand placed on the respiratory muscles is presumably increased as well. It has been shown that the metabolic and circulatory costs of a high work of breathing during maximal levels of ventila-