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YEAR BOOK OF SPORTS MEDICINE®

2010

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2010
The Year Book of SPORTS MEDICINE®

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Journals Represented

Journals represented in this YEAR BOOK are listed below.

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American Journal of Cardiology
American Journal of Clinical Nutrition
American Journal of Emergency Medicine
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New England Journal of Medicine
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Sports Medicine
Stroke
The Clinical Journal of Pain
The Journal of the American Medical Association
The Journal of Bone and Joint Surgery
The Journals of Gerontology
The Spine Journal
Transfusion

Standard Abbreviations

The following terms are abbreviated in this edition: acquired immunodeficiency syndrome (AIDS), cardiopulmonary resuscitation (CPR), central nervous system (CNS), cerebrospinal fluid (CSF), computed tomography (CT), deoxyribonucleic acid (DNA), electrocardiography (ECG), health maintenance organization (HMO), human immunodeficiency virus (HIV), intensive care unit (ICU), intramuscular (IM), intravenous (IV), magnetic resonance (MR) imaging (MRI), ribonucleic acid (RNA), and ultrasound (US).

Note

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Present Role of Maximal Oxygen Intake Measurements in Sports Medicine

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Introduction

The measurement of maximal oxygen intake has been widely accepted as the best single measure of an individual's endurance fitness since the middle of the previous century.[1-4] Indeed, the concept that an individual's oxygen intake reaches a plateau in response to a progressive increase in work rate dates back to A.V. Hill and his associates.[5] A search of the HealthStar-Ovid.database for studies on maximal/maximum oxygen intake/uptake and maximal/maximum aerobic power/capacity reveals a total of some 4798 papers published over the past 60 years. During this period, authors have progressively developed a preference for the grammatically correct term "maximal" rather than "maximum" and the dimensionally correct term "power" (a rate of working) rather than "capacity" (the ability to sustain oxygen transport for a specified period). A vast literature covers potential techniques of measurement, the theoretical significance of observations, and practical applications of the data.

Nevertheless, one can still find occasional studies that question both the existence of an oxygen consumption plateau[6] and the practical value of such testing to the sports physician.[7,8] It thus seems useful to revisit the concept of maximal oxygen intake and to consider its practical value to the sports physician and the exercise scientist. The findings and recommendations of the International Biological Programme (IBP) Working Party provide an appropriate and authoritative starting point for the present discussion.[9]

Findings and Recommendations of the IBP Working Party

Noting the central importance of maximal oxygen intake to studies in sports medicine and exercise science, in the summer of 1966 the IBP convened a working party of the world's leading investigators with the mandate to determine the protocols most appropriate to a variety of field and laboratory situations.[9] Their detailed test recommendations still offer helpful guidance to investigators, particularly those who have found difficulty in demonstrating the classic plateau of oxygen consumption (an increase in oxygen consumption of less than 2 ml/[kg·min] in response to an increase of work rate). Among key requirements, subjects should be well motivated and familar with the laboratory and its equipment, and investigators should follow an appropriate and internationally standardized protocol. Expired gas should be collected using a low resistance, low dead space system, and analyses performed without systematic error. In the era of the IBP Working Party, the Douglas bag technique was used rather than a metabolic cart that includes "black box" calculations of uncertain validity; this approach avoided issues of technical accuracy, sampling time and uncertain methods of calculation that have dogged more recent investigators.[10]

The underlying data were derived from the most comprehensive investigation yet undertaken in the field of stress testing. The subjects were 24 men aged 20 to 40 years, ranging widely in initial fitness (maximal oxygen intake 30.6 to 69.1 ml/[kg·min]). Each participant performed 11 successive maximal oxygen intake tests over a 3-week period, using three different test modalities (treadmill, cycle ergometer, and step test) and both continuous and discontinuous test protocols according to a random block design. All subjects reached a clear oxygen consumption plateau with all three modes of exercise and both types of protocol, thus offering multiple test options to investigators. Nevertheless, on average, treadmill values were 4% higher than those for the step test and 7% higher than those for the cycle ergometer. Values over the 3-week study were highly reproducible but increased by about 1% per day in response to the training stimulus imposed by repeated maximal testing. However, it was also recognized that over a longer time frame, an individual's maximal oxygen intake could change by up to 20% in response to changes in health and training status.[11]

The final arterial lactate values in the IBP trial, although less than the 30 m/L reported after some types of athletic competition,[12] were nevertheless substantially higher than those achieved in some laboratories, for example, 13.7 ± 1.7 and 12.7 ± 2.2 mM/L for the discontinuous and continuous treadmill tests respectively. The IBP data clearly demonstrate that given well-motivated subjects and an appropriate test protocol, young adults consistently reach an oxygen consumption plateau.

Technical Problems in Defining an Oxygen Consumption Plateau

Technical considerations are commonly to blame when there have been difficulties in demonstrating a plateau.[13,14] Specific issues include an inappropriate choice of test protocol, activation of an inadequate muscle mass, a lack of motivation on the part of the subject and/or the observer, specific characteristics of the population tested, and the existence of pathological conditions that lead to a premature termination of effort by the subject or the observer.

Test Protocol

In keeping with other authors,[15-17] the IBP recommended that a maximal oxygen intake test should begin after a 5-minute "warm up" at exercise demanding 50% to 70% of maximal oxygen intake. However, this precaution has not always been observed.[9,18] The definitive test must also be of sufficient duration in order to demonstrate a plateau. The first of a series of discontinuous tests should begin at 110% of the maximal oxygen intake, as estimated from the warmup data; subsequent tests should be set at slightly higher or lower work rates, depending on the subject's response to the first bout of exercise. A duration of 2-6 minutes seems appropriate for discontinuous measurements.[19,20] If a continuous ramp-function protocol is chosen, effort should begin at 90% to 100% of the individual's estimated maximal value; small increments of work rate (treadmill speed and/or slope) are then made in each subsequent 1- to 2-minute interval. The total duration of a continuous test is ideally 8 to 12 minutes,[21] although if the final treadmill slope is not excessive, valid results have been obtained over exercise times varying from 7 to 26 minutes.[9,18] Studies failing to demonstrate a plateau have adopted excessively large increments in the intensity of effort; often the subjects concerned have become exhausted before reaching the exercise intensity where an oxygen consumption plateau is likely to be observed.

Muscle Mass

Activation of an adequate muscle mass is a second important prerequisite for reaching an oxygen consumption plateau. The IBP Working Party suggested that in the average subject, this condition was best satisfied during uphill treadmill running.[9] The muscle volume was less adequate when tests were performed on a standard cycle ergometer; effort was then constrained in part by factors such as peripheral vascular capacity and a local limitation of blood flow through strongly contracting muscles.[9,22–25]

Most categories of athlete have a sport-specific development of their musculature, and their maximal oxygen intake is best measured when they are undertaking actual or simulated sport (using, for instance, pool or flume measurements on a swimmer, and rowing ergometer or telemetric measurements from a boat in the case of an oarsperson).

The relative importance of central (cardiac) and peripheral (muscular) limitations during different forms of exercise has been highlighted by two main approaches. A comparison of single- versus two-leg ergometry.[26] shows that the peak oxygen consumption during one-leg exercise is substantially more than a half of that seen during two-leg effort; in other words, greater perfusion of the leg muscles is possible when most of the cardiac output is directed to a single limb. If the peak oxygen intake when breathing room air is compared with that seen when breathing a gas mixture containing 12% oxygen,[27] the adverse impact of the hypoxic mixture increases in proportion to the volume of active muscle, because with greater muscle involvement the individual's effort is progressively limited by central oxygen transport rather than peripheral factors.

Motivation

Perhaps the most critical element in any measurement of maximal oxygen intake is the motivation of the subject and the investigator. It is essential to push the test participant to ever greater effort in the face of discomfort and a feeling of impending collapse. As the work rate is increased, the cardiac output becomes insufficient to sustain the ever growing demands of both the skeletal muscles and other tissues. The IBP article (p 759) gives a dramatic description of the failing circulation: "subjects complained of nausea, breathlessness and chest pain, looked intensely cyanosed, and in some cases became unsteady on their legs."[9] As early investigators realized,[1] much depends on the individual's determination and sense of physical self-efficacy.[28,29] Thus, ratings of perceived exertion[30,31] and other multidimensional perceptions of fatigue help in deciding whether the subject has made a valid maximal effort.[32] A cursory examination of peak values for secondary criteria such as arterial lactate, respiratory gas exchange ratio and ratings of perceived exertion underlines the problem that motivation has been inadequate in studies where a plateau of oxygen consumption has not been observed.

Population Characteristics

The IBP team recognized that although there were no problems when testing young male subjects, it was more difficult to demonstrate consistent plateau values in other populations such as young children, sedentary women and the elderly.

CHILDREN

Some authors have reported a plateau of oxygen intake in as few as one half[24,33] or one third[24,33] of young children, the likelihood of successful testing being greatest in fit children. One training study found a similar increment of peak oxygen transport in subjects who failed to reach a plateau, although the results for such individuals had a poor reliability.[34] The IBP investigators had the wisdom to invite their representative sample of 47 prepubescent children to the laboratory for a preliminary familiarization session. A single maximal treadmill test was performed at a subsequent visit, and 35 of the 47 subjects then demonstrated a clear oxygen consumption plateau. These subjects made what was judged as either a strenuous (final arterial lactate 11.7 ± 2.0 mM/L in boys, 12.2 ± 3.5 mM/L in girls) or an average effort (8.1 ± 0.3 mM/L in boys, 8.0 ± 0.5 mM/L in girls), and their final oxygen consumption values showed no systematic deviation from the maxima predicted from submaximal data. Comparable final lactate levels were observed by Åstrand,[33] but peak lactates were much lower in some recent reports (for instance, 5.4-6.5 mM/L in one study).[34] In the remaining 12 children who participated in the IBP study, effort was judged as inadequate; their terminal arterial lactate concentrations were 6.7 mM/L or less, and their peak oxygen intake values were substantially less than predicted from submaximal testing.

ELDERLY SUBJECTS

Some authors have found no difficulty in testing older adults. Shephard and Sidney[35] examined the ability of seniors as old as 83 years to undertake maximal oxygen intake testing. The usual criterion of an oxygen consumption plateau was well satisfied by 18 of 26 elderly men and 19 of 29 elderly women (respective plateau readings of 0.5 ± 1.8 and 0.8 ± 1.4 mL/[kg·min], and final arterial lactate readings of 12.3 ± 3.7 and 10.1 ± 2.2 mM/L. The 18 individuals who failed to reach a plateau could readily be distinguished by subjective ratings of the quality of effort, a lower peak heart rate, a lower respiratory gas exchange ratio, and a lower final arterial lactate concentration (6 to 7 mM/L). Moreover, about a half of the individuals thus identified were able to reach a plateau at their second attempt.[35]

CONCLUSIONS

In young children and elderly subjects, a minority of individuals fail to reach the usually accepted definition of an oxygen consumtion plateau. However, such individuals can be identified fairly readily by a subjective rating of their motivation and objective measures of the effort that they achieved, particularly the final arterial lactate concentration, but including also peak heart rate and respiratory gas exchange ratio.

Pathological Conditions

One study demonstrated an oxygen consumption plateau in 20 of 36 patients undergoing rehabilitation following myocardial infarction.[36] Nevertheless, in many patients with cardiovascular disease, maximal effort may be halted by warning symptoms or signs,[37] such as irregularities of heart rhythm, depression of the ST segment of the electrocardiogram, and an excessive rise or a fall of blood pressure before an oxygen consumption plateau has been attained. The value thus observed is termed a peak rather than a maximal oxygen intake. As discussed below, the information may still have clinical value, particularly when setting an appropriate exercise prescription for the patient concerned.

Theoretical Basis of Oxygen Consumption Plateau

An analysis of oxygen concentrations along the transport chain from the lungs to the mitochondria[38,39] suggests that the efforts of both endurance athletes and more sedentary individuals are normally limited by circulatory factors.[40,41] However, in some circumstances peripheral influences such as muscle capillarity, the diffusion of oxygen from the capillaries to the mitochondria, and even the ability of the mitochondria to utilize oxygen can become the main limiting factor.[42,43] Poor motivation, the learning of competitive tactics or a failure of cerebral blood flow can also lead to a central limitation of neuromuscular drive.[44,45]

If a large muscle volume is activated, as in uphill treadmill running, then the maximal blood flow to the peripheral tissues is certainly the primary constraint.[46,47] The dominance of circulatory factors is strongly supported by a mathematical analysis of conductances in the oxygen transport chain.[38] However, top-level athletes sometimes show ventilatory limitations, with a significant decrease of arterial oxygen saturation during maximal effort.[48,49] The restrictions imposed by a finite pulmonary diffusing capacity of some 600 $mL \cdot min^{-1} kPa^{-1}$ are exacerbated by exposure to high altitudes, and by any trend to pulmonary edema during prolonged effort.[50] On occasion, an endurance athlete may also be limited by an inadequate circulatory transport of oxygen or glucose to the motor cortex, with a resulting failure of the motoneurons.[41,51]

If the volume of active muscle is small (for example, during arm ergometry), the critical factor limiting an 8- to 12-minute bout of exercise becomes a local accumulation of lactate in the working muscles; this progressively hampers the resynthesis of ATP and creatine phosphate.[43] Finally, in self-paced or poorly motivated effort, limits may be imposed by the individual's willingness to activate the neurons of the motor cortex.[45] Particularly during prolonged effort, athletes deliberately hold effort over most of an event to a level that minimizes lactate accumulation in the active muscle.

Factors Limiting Cardiac Output

The plateauing of oxygen intake with increasing effort normally occurs at or near maximal steady-state heart rate. Stroke volume plateaus at a lower intensity of effort, and it may actually show some decline as peak effort is approached. If a relatively small muscle mass is activated, a further consideration is the ability of the peripheral vasculature to accept the available blood flow without provoking an excessive rise of blood pressure.

HEART RATE

Many authors have found a plateauing of heart rate either before[9,52] or immediately following a plateauing of oxygen consumption.[35,53–55] The reason for the ceiling of steady-state heart rates remains unclear. Substantially higher values can be reached for brief periods (for instance, during a ski turn). Lower maxima are seen both at altitude and in the elderly; this might seem to indicate an influence of local oxygen lack upon the myocardium, as suggested by A.V. Hill.[5] But against this hypothesis, the administration of oxygen does not bring peak heart rates to the levels seen in young adults at sea level. Possibly, problems of diastolic filling may be involved, or baroreceptor reflexes may be activated by rising pressures in the systemic and pulmonary circulation; prolonged exercise also reduces the heart rate response to catecholamines.[44]

STROKE VOLUME

Changes of cardiac stroke volume with exercise depend on the individual's posture. During supine exercise, there may be little increase over resting values; however, in the upright position stroke volume increases progressively until the individual reaches the optimal part of the Frank-Starling curve, commonly around 70% of maximal oxygen intake.[56] In young adults, the stroke volume may then continue relatively unchanged through to maximal effort,[57-59] but in elderly subjects, the stroke volume sometimes decreases as maximal effort is approached.[60] This could reflect a limitation of venous return and/or impaired venous filling at rapid heart rates,[61] or changes in myocardial contractility.[62]

OTHER FEEDBACK AND FEED-FORWARD CONTROLS

A variety of feedback and feed-forward controls can sometimes limit maximal cardiac output, and thus the transport of oxygen and nutrients needed for aerobic activity. Plainly, the stroke volume diminishes if a lack of venous return or a slow relaxation of the ventricles restricts diastolic filling. At the opposite end of the spectrum, an excess of diastolic filling pushes the heart muscle beyond the optimum point on the Frank-Starling curve, with a resulting decrease in myocardial contractility. The ejection fraction may be diminished further by the rising systolic pressure. A further potential restraint is the resistance to myocardial distension imposed by the pericardium.[63]

The circulation is regulated against an excessive rise of either systemic or pulmonary blood pressure by feedback from the baroreceptors, with additional influences from the central vasomotor centers, the muscle pressor reflex and central blood volume receptors.[64,65]

As cardiac output reaches its limiting value, the supply of oxygen and glucose to the brain may become inadequate. This leads to a failure of muscle coordination, a reduction of neuromuscular drive, and ultimately a loss of consciousness.

Finally, if the volume of active muscle is small, an inadequate peripheral circulation leads to a progressive accumulation of lactate; this in turn causes muscular pain and further effort is inhibited because the resynthesis of ATP and creatine phosphate is compromised.

Practical Uses of Maximal Oxygen Intake Measurements in Sports Medicine and Exercise Science

The practical applications of maximal oxygen intake measurements include objective determinations of habitual physical activity and resulting levels of aerobic fitness, prescribing appropriate intensities of exercise and training, assessing responses to conditioning programs, evaluation of the aerobic demands of various sports and the condition of individual participants, determination of the ergogenic potential of various drugs and procedures, the monitoring of over-training and rehabilitation, and specific clinical applications such as the prediction of prognosis and defining safe levels of exercise for those with cardiorespiratory disease.

Habitual Physical Activity and Aerobic Fitness

Accurate determinations of habitual physical activity are a pre-requisite when assessing the current fitness of populations,[2,4,66] examining secular trends in their fitness and lifestyle,[67] looking at the effectiveness of various community and work-site health promotion initiatives[68,69] and determining possible relationships between physical activity and the risks of various types of chronic disease.[4,70] Aerobic power measurements are also important when examining the ability of people to engage in various types of physically demanding occupations at various ages; such information is frequently required in discussions of equal opportunity in employment.[71]

Unfortunately, available physical activity questionnaires are notoriously inaccurate, and simple activity measuring instruments such as pedometers and accelerometers also fail to capture many significant sources of energy expenditure.[72] For this reason, it is preferable to base most analyses on the individual's response to regular aerobic activity, as shown by the level of his or her maximal oxygen intake; associations with health outcomes such as all-cause mortality are much stronger for measurements of aerobic