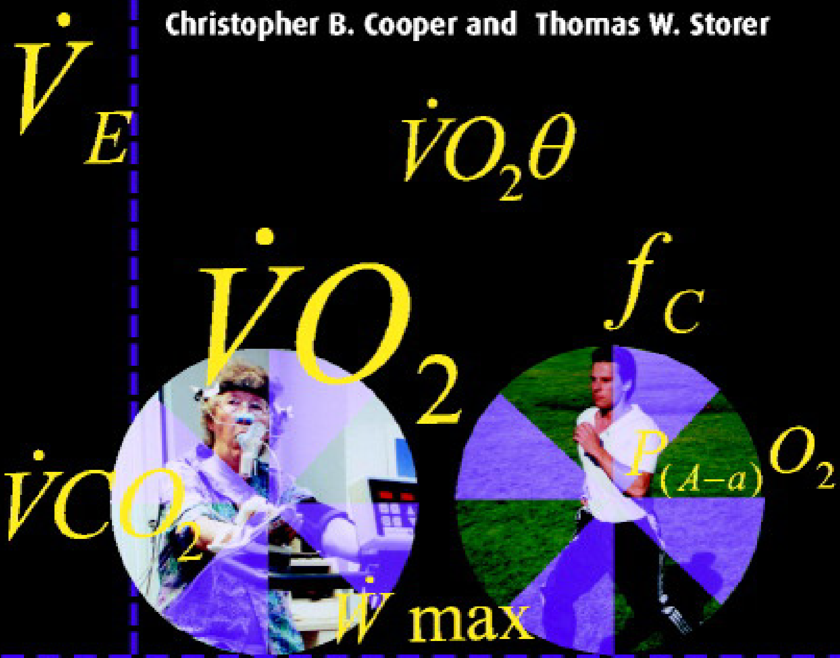
Exercise testing and interpretation

A practical approach

Christopher B. Cooper and Thomas W. Storer



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In *Exercise Testing and Interpretation: A Practical Approach*, Drs Christopher Cooper and Thomas Storer offer a practical and systematic approach to the acquisition, interpretation, and reporting of physiologic responses to exercise.

Pulmonologists, cardiologists, and sports physicians, as well as respiratory therapists and other allied health professionals, will find this book an indispensable resource when learning to select proper instruments, identify the most appropriate test protocols, and integrate and interpret physiologic response variables. The final chapter presents clinical cases to illuminate useful strategies for exercise testing and interpretation. Useful appendices offer answers to frequently asked questions, laboratory forms, algorithms, and calculations, and a glossary of terms, symbols, and definitions. *Exercise Testing and Interpretation: A Practical Approach* offers clearly defined responses (both normal and abnormal) to over 40 performance variables including aerobic, cardiovascular, ventilatory, and gas exchange variables.

Practical, portable, and easy-to-read, this essential guidebook can be used as a complement to more detailed books on the topic, or stand on its own.

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Dedicated to Nancy and Paula

''Those who do not make time for exercise will eventually have to make time for illness''

The Earl of Derby (1863)

Contents

Preface

Exercise is fundamental to human existence. For most men and women exercise is essential for quality of life and for many it is the essence of their livelihood. Some have a competitive instinct for athletic performance in the pursuit of individual human achievement. We now understand that the maintenance of physical fitness throughout life is crucial if we are to remain healthy and live to an advanced age. In these contexts, the assessment of exercise ability is of considerable importance to humanity. Exercise testing becomes the means of assessing ability to perform specific tasks, quantification of athletic performance, diagnosis of disease, assessment of disability, and evaluation of responses to physical training, therapeutic intervention, and rehabilitation.

Recent years have indeed witnessed widespread applications of exercise testing that range from clinical uses in assessing debilitated patients to sports medicine venues and the testing of élite athletes. Some exercise tests are appropriately performed with a minimum of equipment, such as a watch and a measured course. Others involve more sophisticated instrumentation enabling more detailed assessments. Advances in technology have rendered all exercise tests more accessible and more affordable, although not necessarily easier to perform with accuracy and reliability. Wireless heart rate monitors give instantaneous and reliable heart rates in the field or in the laboratory. Bi-directional, light-weight, mass flow sensors have obviated the need for cumbersome valves and tubing and, together with miniaturized and fast-responding gas analyzers, enable the calculation of oxygen uptake with every breath. Computer technology has revolutionized the real-time acquisition and analysis of data, although not necessarily made exercise tests any easier to interpret.

We have both practiced and taught in the field of exercise testing and interpretation for many years. We saw the need for a practical text that succinctly explains the physiology of exercise and also gives detailed advice regarding the conduct and interpretation of exercise tests in a variety of settings. We have included clinical and sports medicine applications because we are convinced that these disciplines will merge in the future. We have addressed technical considerations, pitfalls, and solutions. We have placed emphasis on creative figures and diagrams to offer systematic explanations and schemata for interpretation. We have also attempted to address the confusion that surrounds terminology in this diverse field. We have done so through a systematic, logical, and critical examination of the concepts and applications of the field. We hope our approach is enlightening and not a mere addition to the plethora of terms and symbols already in use.

Exercise testing, which we abbreviate to XT, can be conducted for several purposes, in a variety of settings. *Performance* exercise tests (PXT) can be performed in the *field* or *laboratory* using a selection of protocols, depending upon the purpose of the test. Typicaly, PXT are conducted to establish exercise-training guidelines and to monitor progress. *Clinical* exercise tests (CXT) have a somewhat different emphasis and are almost exclusively conducted in a laboratory setting. CXT can be *diagnostic*, seeking an explanation for exercise impairment; for *risk assessment*, such as from coronary artery disease or surgery; or alternatively for *monitoring*, for example to quantify the response to therapeutic or surgical interventions or to document progress in rehabilitation. Exercise capacity can be measured by different protocols ranging from the time required to complete a measured course to the acquisition of a wide range of cardiovascular, ventilatory, and gas exchange variables. *Functional* exercise tests focus on ability to perform a specific task whereas *integrative* exercise tests compile an array of variables with which to study the underlying physiology of the exercise response.

Several features of this book are unique. The core of the book describes instrumentation and protocols for exercise testing followed by response variables and their interpretation. The book is laid out so that the reader can easily locate a piece of equipment or response variable for ready reference. Chapter 2 (Instrumentation) describes apparatus for exercise testing explaining, succinctly, the principles of operation and essential facts about calibration and maintenance of the equipment. Chapter 3 (Testing methods) describes protocols for exercise testing with many important details, gleaned from years of experience, that facilitate a successful test. Chapter 4 (Response variables) expands on the many physiological variables that can be derived from exercise testing, ranging from simple timed distances to the complex integrated cardiovascular and gas exchange variables which underlie the exercise response. Each variable has its own section including a definition, derivation, and units of measurement, along with examples of the normal and abnormal responses. Chapter 5 (Data integration and interpretation) presents a novel and systematic approach to help the reader develop a confident and meaningful interpretation of the data. There is an emphasis here on integrative exercise testing because interpretation of this type of XT has often presented more problems to the exercise practitioner. Chapter 6 illustrates the principles expounded in Chapters 2 through 5 with a selection of real cases. Finally, the appendices are designed to be a valuable resource for the exercise practitioner. They include a glossary of proper terms and symbols as adopted by exercise physiologists, simplified algorithms to help explain the derivation of secondary variables, predicted normal values with appropriate critique, examples of worksheets that facilitate testing, and a section on frequently asked questions.

Finally, a few words about the units of measurement incorporated in this book. Our goal has been to write a book that will be of practical value to persons throughout the world who are involved in exercise testing and interpretation. As such we have had to deal with certain inconsistencies in currently accepted units of measurement. Some countries, including the USA, continue to use imperial rather than metric units for certain measurements. The *Système International d'Unités* attempts to bring everyone into concordance with a metric system. However, some traditional units do not lend themselves comfortably to this conversion. We have used SI units wherever possible but referred to traditional units as well when conversion was not straightforward. Readers will undoubtedly find some inconsistencies and discrepancies but hopefully these can always be resolved by reference to Table B1 in Appendix B which explains any necessary conversions.

This book is intended to be a practical text which exercise practitioners would want readily available in their clinical or research laboratories, rehabilitation facilities, and sports clubs. The book may prove useful for chest physicians, cardiologists, exercise physiologists, occupational health physicians, sports physicians, sports scientists, laboratory technicians, physical or respiratory therapists, medical students, and postgraduate students in the exercise sciences. The material for the book has evolved over many years of teaching exercise physiology, exercise testing, and interpretation. Parts of the book reflect a syllabus that we have developed and refined over the past eight years for an annual symposium that has taken place at UCLA as well as several national and international venues. Reflecting our own careers and experiences, we have tried to approach the topic simultaneously from the perspectives of exercise science and clinical medicine. By doing so we have attempted to develop a comprehensive and balanced view of a complex subject which we hope will appeal to, and draw together, a broad range of disciplines with a common purpose – that of understanding the human exercise response.

CBC, TWS
Los Angeles, California

Acknowlegments

This book has evolved from what we have learnt from our mentors, students, and patients. However, its production owes much to the support of others. We wish to thank the staff at Cambridge University Press, particularly Jocelyn Foster who was involved at the conception of the project and Liz Graham who undertook the formidable task of copyediting. We are especially indebted to Judy Valesquez for her meticulous preparation of the figures. Finally, we must acknowledge our families for accepting the many hours we were not with them.

CBC, TWS

1

Purpose

Introduction

The human body is designed for the performance of exercise. Habitual patterns of exercise activity are known to be linked to health, well-being, and risk of disease. In fitness and athletics, exercise capacity is linked to performance and achievement. In clinical medicine, exercise performance is intricately related to functional capacity and quality of life. Hence the importance of exercise testing and interpretation as a means of determining exercise capacity and identifying factors which might limit exercise performance. Exercise professionals, whether concerned with physical fitness and sports or clinical medicine and rehabilitation, should be well versed in methods of exercise testing and interpretation. Hence the need for a practical guide to assist in this undertaking.

A wide variety of methods have evolved for the purpose of assessing exercise capacity and identifying specific limiting factors. Field tests are commonly used in fitness and sports to assess athletic performance, but can be used to assess progress in clinical or rehabilitative settings. Laboratory exercise protocols are also used to assess fitness and are often combined with electrocardiography to diagnose coronary artery disease. Symptom-limited, incremental exercise testing, including measurement of ventilation and gas exchange, has proven to be an important diagnostic, clinical, prescriptive, and rehabilitative tool. These more complex laboratory tests evaluate the integrated human cardiovascular, ventilatory, and musculoskeletal responses to exercise. Whether the assessment is conducted in the field or in the laboratory, all of these exercise tests require careful attention to detail if meaningful information is to be derived.

This book provides a detailed examination of the instruments, methods, proper conduct, and interpretation of a variety of exercise tests. This is meant to be a practical guide, assisting the reader in every step of the process with fundamental information, examples, and practice using a time-tested methodology. The next section of this chapter reviews the basic exercise physiology that underlies exercise testing and interpretation. It is included not as a primer, but rather to illustrate the important concepts involved.

Basic exercise physiology

Coupling of cellular respiration to external work

During the performance of most types of exercise, it is well known that oxygen uptake ($\dot{V}O_2$) is tightly coupled to external work rate ($\dot{W}$) or power output. The essential components of this coupling are illustrated in Figure 1.1. Central to our understanding of exercise physiology is the measurement of alveolar oxygen uptake ($\dot{V}O_{2alv}$) by collection and analysis of exhaled gases. $\dot{V}O_{2alv}$ provides the systemic arterial oxygen content for delivery to exercising muscles. Hence, the extent to which $\dot{V}O_{2alv}$ matches muscle oxygen consumption ($\dot{Q}O_{2mus}$) is in part a reflection of the effectiveness of oxygen delivery via the

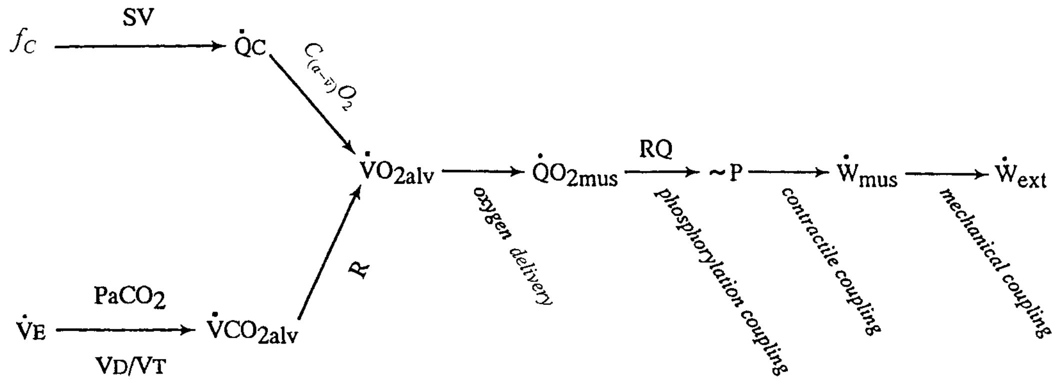

Figure 1.1 Cardiovascular and ventilatory coupling to external work. See the accompanying text and Appendix A for definitions of the symbols.

circulation. In steady-state conditions $\dot{V}o_{2alv}$ should reflect the oxygen consumption of all tissues, including $\dot{Q}o_{2mus}$. However, in unsteady-state conditions, such as during an incremental exercise test or during the transition from rest to constant work rate exercise, changes in $\dot{V}o_{2alv}$ typically lag behind changes in $\dot{Q}o_{2mus}$. In exercising muscle oxygen is utilized in the production of high-energy phosphate compounds (*~P*). The yield of *~P* per oxygen molecule is dependent on the substrate being utilized for energy generation, which in turn dictates the respiratory quotient (RQ) of the muscle tissue. The conversion of chemical energy in the form of *~P* to intrinsic muscle work ($\dot{W}_{mus}$) depends on contractile coupling and mechanisms that result in actin–myosin cross-bridge formation and muscle shortening. Finally comes the conversion of $\dot{W}_{mus}$ to external work ($\dot{W}_{ext}$), which can be measured by an ergometer. This last stage has a significant effect on work efficiency, being influenced by musculoskeletal coordination and undoubtedly incorporating a skill factor. Aside from the choice of substrate and the skill factor, it can be appreciated that the sequence of mechanisms described above is largely defined by immutable metabolic reactions and ultrastructural properties of human skeletal muscle. Not surprisingly, therefore, when a short-duration exercise protocol which utilizes carbohydrate as the predominant metabolic substrate is performed on a cycle ergometer which minimizes the skill factor, the relationship between $\dot{V}o_{2alv}$ and $\dot{W}_{ext}$ demonstrates linearity and remarkable consistency among normal subjects (see Chapter 4).

Cardiopulmonary coupling to external work

Integrated exercise testing usually attempts to study the simultaneous responses of the cardiovascular and pulmonary systems. Commonly the cardiovascular response is judged by changes in heart rate (f_C) with respect to measured $\dot{V}o_2$ whereas the pulmonary response is judged in terms of minute ventilation ($\dot{V}_E$). Figure 1.1 illustrates how each of these variables is coupled to $\dot{V}o_2$.

Cardiac output ($\dot{Q}_C$) is of central importance in the cardiovascular coupling. The Fick equation (see Chapter 4) reminds us that the relationship between $\dot{Q}_C$ and $\dot{V}o_2$ is determined by the difference in oxygen content between systemic arterial blood and mixed systemic venous blood ($C_{(a-\bar{v})}o_2$). Obviously $\dot{Q}_C$ and f_C are linked through cardiac stroke volume (SV).

Carbon dioxide output ($\dot{V}co_2$) is of central importance in ventilatory coupling. The Bohr equation (see Chapter 4) reminds us that the relationship between $\dot{V}co_2$ and $\dot{V}_E$ is determined by the level at which arterial carbon dioxide tension ($Paco_2$) is regulated and the ratio of dead space to tidal volume (V_D/V_T). Obviously alveolar $\dot{V}co_2$ and $\dot{V}o_2$ are linked by the respiratory exchange ratio, *R*.

Metabolic pathways

This book will not attempt a detailed description of all of the metabolic pathways involved in exercise. However, a simplified description of cellular energy generation follows and is illustrated in Figures 1.2 and 1.3.

Whilst fat and protein degradation can sometimes be important in the metabolic response to exercise, undoubtedly the principal substrate for muscle metabolism is carbohydrate in the form of muscle glycogen. The degradation of glycogen to pyruvate occurs in the cytosol and is termed anaerobic glycolysis or the Embden–Meyerhof pathway (Figure 1.2). Firstly, glycogen must be split into glucose units by a glycogen phosphorylase. Each molecule of glucose is then converted to two molecules of pyruvate, with the net generation of two ATP molecules and four hydrogen ions. The hydrogen ions are taken up by the coenzyme NAD to form $NADH + H^+$.

Pyruvate undergoes oxidative decarboxylation that irreversibly removes carbon dioxide and attaches the remainder of the pyruvate molecule to coenzyme A (CoA), forming acetyl-CoA. Note that acetyl-CoA is also the product of fatty acid β-oxidation. Acetyl-CoA enters the mitochondrion and combines with oxaloacetate to become citrate. In this way acetyl-CoA becomes fuel for the tricarboxylic acid (TCA) cycle, otherwise known as the Krebs cycle or citric acid cycle (Figure 1.2). This sequence of enzymatic reactions dismembers acetyl-CoA, yielding carbon dioxide and hydrogen atoms. Once again the hydrogen ions are accepted by coenzymes. For every acetyl unit consumed in the cycle, there are two carbon dioxide molecules produced along with three $NADH + H^+$ and one $FADH_2$. In addition there is one directly produced molecule of GTP which contains an equivalent amount of energy to ATP. Note that by accepting hydrogen ions the coenzymes NAD and FAD play a vital role in trapping energy.

The main engine for cellular energy generation is the mitochondrial pathway for oxidative phosphorylation, which is shown in Figure 1.3. This pathway is also called the respiratory chain or electron transport chain. The chain is a complex device consisting of lipoproteins with different cytochromes, metals, and other cofactors. Essentially, the chain facilitates the flow of electrons from coenzymes $NADH + H^+$ and $FADH_2$ releasing energy for the phosphorylation of ADP to ATP at three sites. Finally, two electrons are combined with two protons (H^+) and oxygen to form water. $NADH + H^+$ enters the first stage of the chain, giving rise to NAD and three ATP, whereas $FADH_2$ enters the second stage of the chain, giving rise to FAD and two ATP. The oxidized coenzymes are released and become available to catalyze dehydrogenase reactions further.

Summarizing all of the pathways described above, the usual process of cellular energy generation can be described by two equations:

$$NADH + H^+ + \tfrac{1}{2}O_2 + 3Pi + 3ADP \rightarrow 3ATP + NAD + H_2O \tag{1.1}$$

$$FADH_2 + \tfrac{1}{2}O_2 + 2Pi + 2ADP \rightarrow 2ATP + NAD + H_2O \tag{1.2}$$

Complete combustion of one molecule of glucose in the presence of sufficient oxygen leads to the generation of approximately 36 molecules of ATP. This number varies depending on how one views the degradation of glycogen and to what extent energy is consumed transporting protons from anaerobic glycolysis into the mitochondrion. $NADH + H^+$ does not cross the mitochondrial membrane and therefore its protons are transferred by a ‘‘shuttle’’ to FAD which enters the electron transport chain at the second rather than the first stage.

When oxygen is not available in sufficient quantity for complete oxidative phosphorylation, then several important changes ensue:

1. The mitochondrial pathways, including the TCA cycle and electron transport chain, are ineffective.
2. Pyruvate accumulates in the cytosol and is converted to lactate.
3. The regeneration of ATP from ADP slows by a factor of approximately 18.
4. Muscle glycogen is more rapidly consumed.

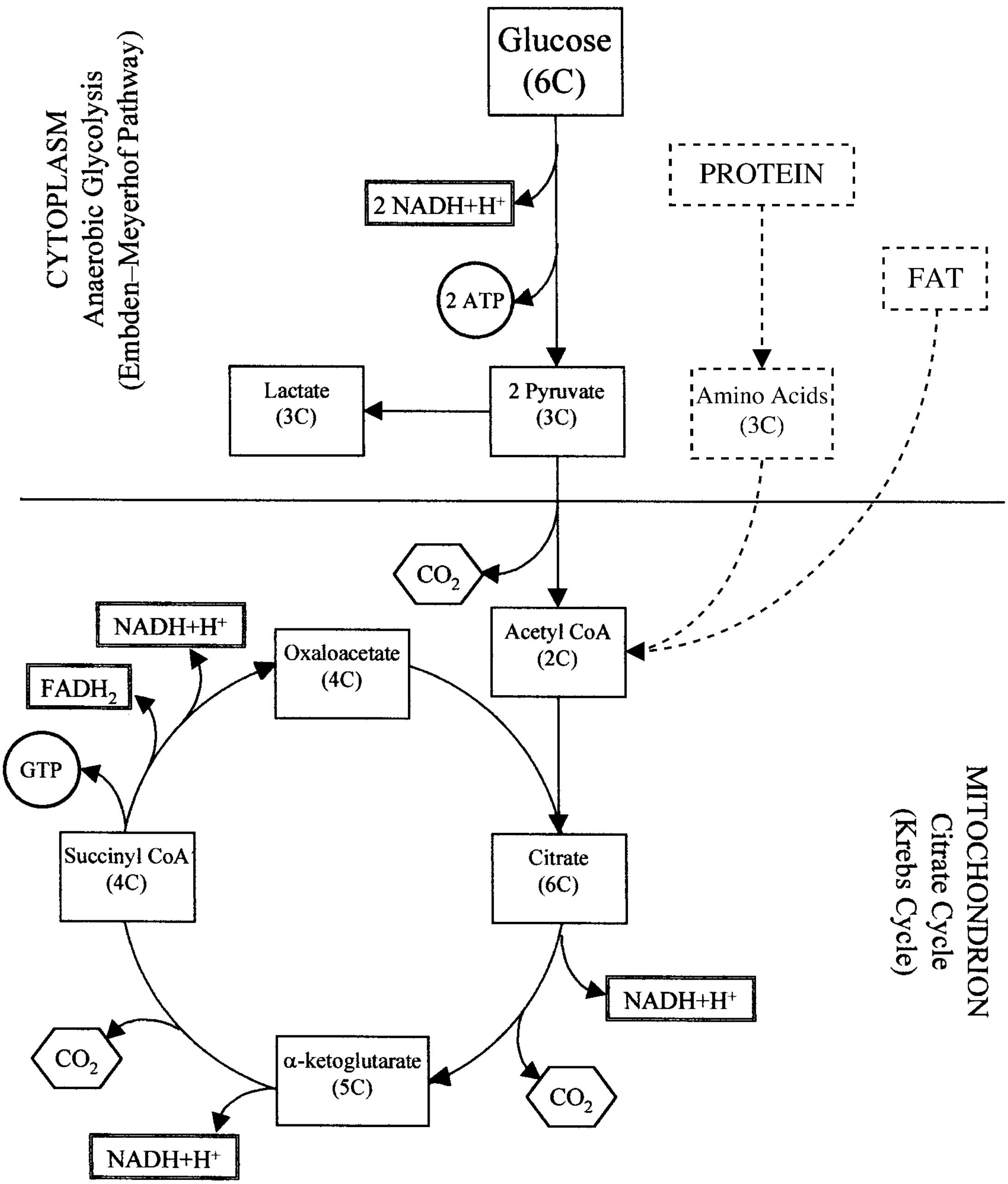

Figure 1.2 Metabolic pathways for cellular energy generation showing anaerobic glycolysis in the cytoplasm and the citrate cycle in the mitochondrion.

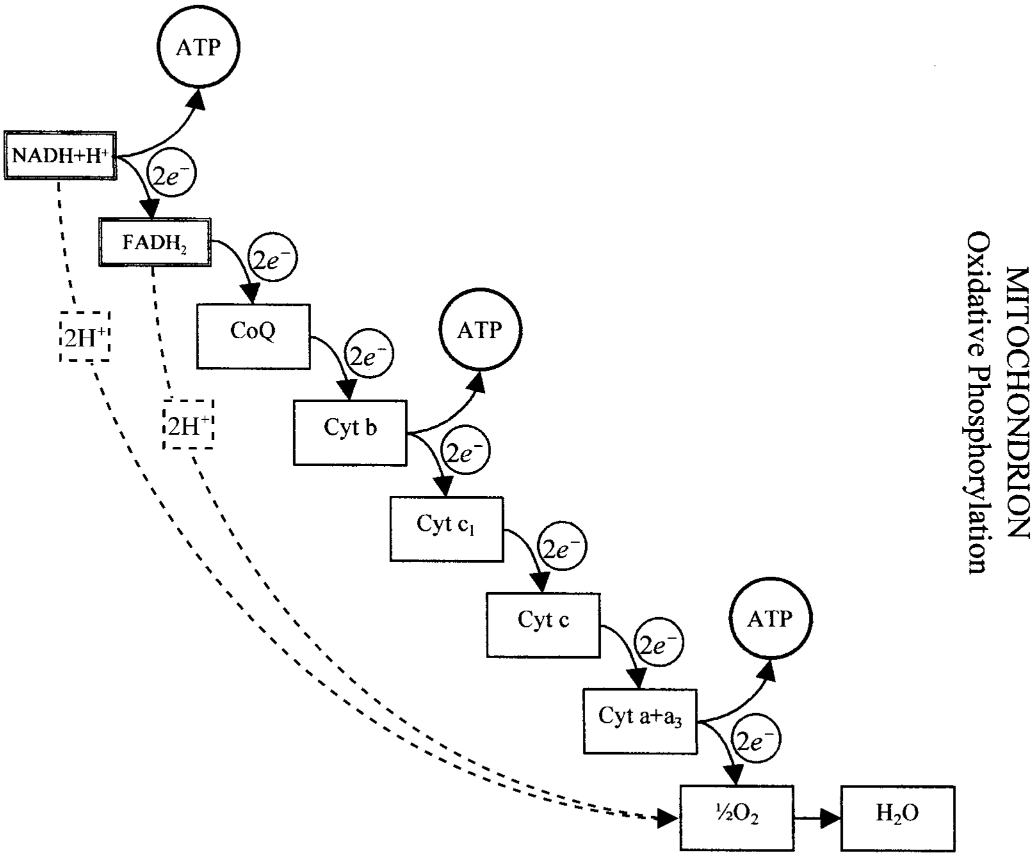

Figure 1.3 Schematic representation of the mitochondrial electron transport chain.

5. Lactate effluxes into the plasma where bicarbonate buffering generates carbon dioxide.
6. Gas exchange and ventilatory changes occur in response to the need to eliminate the additional carbon dioxide.

A compromised ability to regenerate ATP from ADP by oxidative phosphorylation leads to the accumulation of ADP. In these circumstances the myokinase reaction can combine two ADP molecules to create one ATP molecule and one AMP molecule (see Equation 1.3). AMP is then degraded by the action of the enzyme myoadenylate deaminase to create inosine and ammonia (see Equation 1.4).

$$2ADP \rightarrow ATP + AMP \qquad (1.3)$$

$$AMP \rightarrow Inosine + NH_3 \qquad (1.4)$$

These secondary pathways of ATP regeneration seem to be invoked in various clinical conditions which result in cellular energy deprivation.

Aerobic and anaerobic metabolism

Considerable controversy surrounds the use of the terms aerobic and anaerobic to describe the physiological responses to exercise because of the temptation to associate anaerobic metabolism simplistically with insufficient oxygen uptake by the body. During incremental exercise there is not a sudden switch from aerobic metabolism to anaerobic

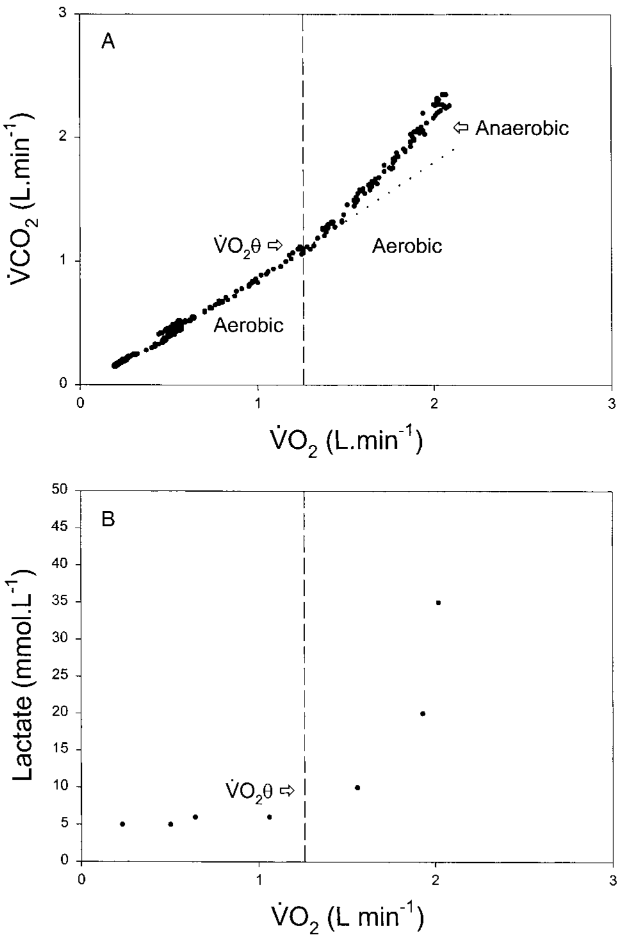

Figure 1.4 Physiological domains of exercise showing the contribution of aerobic and anaerobic metabolism to gas exchange. (A) Changes in $\dot{V}co_2$ with increasing $\dot{V}o_2$. (B) Corresponding increase in blood lactate. $\dot{V}o_2\theta$ is the metabolic threshold separating the aerobic from the aerobic plus anaerobic domains.

metabolism when the supply of oxygen runs short. Nevertheless, it is possible to distinguish two different domains of exercise intensity.

Lower-intensity exercise predominantly utilizes aerobic metabolic pathways, including oxidative phosphorylation for the regeneration of ATP. A small amount of lactate is formed in exercising muscle but blood lactate levels remain low and stable due to effective lactate disposal in other tissues. Constant work rate exercise of this intensity can be performed for long periods without fatigue and the physiological parameters of the exercise response exhibit a steady state.

By contrast, higher-intensity exercise utilizes a combination of aerobic and anaerobic metabolism in order to produce sufficient quantities of ATP. A sustained increase in blood lactate occurs, resulting in a measurable increase in carbon dioxide output derived from bicarbonate buffering, as illustrated in Figure 1.4. In other words, the physiological parameters of the exercise response do not achieve a steady state. A distinction between these two physiological domains of exercise intensity can often be made using noninvasive gas exchange measurements.

In summary, two domains of exercise intensity can be identified and, for the purposes of exercise testing and interpretation, it is helpful to consider the transition between these domains as a metabolic threshold. At the same time the terms aerobic and anaerobic should be used strictly to describe metabolic processes which respectively use oxygen or do not use oxygen regardless of its availability.

Threshold concepts

Incremental exercise testing in a variety of circumstances is likely to reveal not only limitations to maximal performance but also certain thresholds of exercise intensity below or above which different physiological or pathological factors influence the exercise response. Some of these thresholds might be clear-cut. Others will be represented by more gradual transitions. The preceding discussion indicates that the transition from an exercise domain where metabolism is predominantly aerobic to a domain where anaerobic metabolism plays an increasing role is not necessarily clear-cut. However, for the purposes of exercise test interpretation, definition of this threshold has practical value. This is true for exercise tests that assess physical performance in apparently healthy subjects as well as tests which attempt to define exercise limitations in pa-

Table 1.1. Energetic properties of different metabolic substrates relevant to the exercise response

Substrate	Respiratory quotient	Efficiency of energy storage ($kcal \cdot g^{-1}$)	Caloric equivalent for oxygen ($kcal \cdot l^{-1}$)	Caloric eqivalent for carbon dioxide ($kcal \cdot l^{-1}$)
Carbohydrate	1.00	4.1	5.05	5.05
Fat (e.g., palmitate)	0.71	9.3	4.74	6.67
Protein	0.81	4.2	4.46	4.57

tients with illness. Other clinical thresholds of practical importance in patients with cardiovascular or pulmonary diseases undergoing exercise rehabilitation are described below in the section on exercise prescription.

Energetics and substrate utilization

This section on basic exercise physiology concludes with a brief consideration of cellular energetics and substrate utilization. Whatever the substrate being used for muscle metabolism during exercise, it is important to consider the related processes of cellular energy generation both in terms of their efficiency and also the gas exchange and ventilatory consequences for the exercise response. Firstly, let us consider the chemical equations that define the complete oxidation of carbohydrate (glucose) and a fat (palmitate) in the presence of sufficient oxygen, to carbon dioxide and water.

For glucose:

$$C_6H_{12}O_6 + 36ADP + 36Pi + 6O_2 \rightarrow 6CO_2 + 6H_2O + 36ATP \quad (1.5)$$

For palmitate:

$$C_{15}H_{31}COOH + 129ADP + 129Pi + 23O_2 \rightarrow 16CO_2 + 16H_2O + 129ATP \quad (1.6)$$

These equations enable calculations of the respiratory quotient (RQ, or $\dot{V}co_2$ divided by $\dot{V}o_2$), the efficiency of energy storage, and the caloric equivalents for oxygen and carbon dioxide of each metabolic substrate, as shown in Table 1.1. The corresponding values for protein are also included.

These different respiratory quotients are well known. Table 1.1 shows that fat is almost twice as efficient as a storage medium for energy as compared with both carbohydrate and protein. The caloric equivalents for oxygen indicate that carbohydrate is the most efficient substrate in terms of energy generation for every liter of oxygen used in its combustion. Work efficiency during an incremental exercise test, as illustrated by the relationship between external work rate ($\dot{W}$) and $\dot{V}o_2$ is clearly related to the caloric equivalent for oxygen of the substrate or substrates being metabolized during the study. Finally, the caloric equivalents for carbon dioxide serve as a reminder that fat generates less carbon dioxide than carbohydrate and should therefore demand a smaller ventilatory response.

Exercise test nomenclature

Many terms have been used to describe exercise tests leading to some confusion with the nomenclature. However, exercise testing can be conveniently partitioned into two general disciplines, two principal settings and numerous specific protocols (Figure 1.5). The discipline, setting, and protocol of the exercise test should be appropriate for the purpose of the test with the intention of deriving the desired information with the greatest ease and fidelity. The two general exercise test disciplines are performance exercise testing (PXT) and clinical exercise testing (CXT). A PXT is usually performed on apparently healthy individuals for the purposes of quantification of aerobic capacity or fitness assessment, exercise prescription, and response to training or

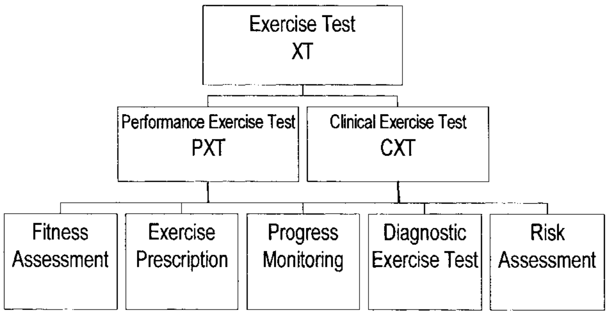

Figure 1.5 A classification for exercise testing distinguishing performance exercise tests for healthy individuals from clinical exercise tests used for the evaluation and management of patients.

lifestyle modification. A CXT is performed on subjects presenting with symptoms and signs of disease for the purposes of diagnosis, risk assessment, progress monitoring, and response to therapeutic interventions. The setting for both PXT and CXT can be in the field or in the laboratory. The convention displayed in Figure 1.5 will be used throughout this book. Chapter 3 describes detailed methods for a variety of field and laboratory exercise tests within these categories.

Evaluation of the exercise response

An exercise response might be judged normal or abnormal on the basis of one or more specific variables or based on a range of variables, which together constitute a physiological response pattern. The extent of this analysis clearly depends on what type of exercise test has been performed, how much data is available, and what the normal response would be expected to resemble. A normal response can be identified in the context of a true maximal or submaximal effort. On the other hand, when abnormalities are identified they need to be characterized according to certain recognized abnormal exercise response patterns (Table 1.2).

A detailed analysis of abnormal exercise response patterns is illustrated in Chapter 5. Cardiovascular limitation is normal, but when it is associated with an abnormal cardiovascular response pattern or impaired oxygen delivery, this points to diseases of the heart or circulation, or perhaps the effects of medications. Ventilatory limitation is usually abnormal and points to diseases of the lungs or respiratory muscles. Occasionally, one sees failure of ventilation due to abnormal control of breathing. With more sophisticated types of exercise testing, abnormalities of pulmonary gas exchange can be identified. This type of abnormality generally points to diseases of the lungs or pulmonary circulation. Reduced aerobic capacity and impairments of the metabolic response to exercise can be due to abnormalities of muscle metabolism due to inherited or acquired muscle disease. Finally, abnormal symptom perception can be associated with malingering or psychological disturbances. Figure 1.6 summarizes the principal categories of exercise limitation and indicates how many common conditions and diseases impact cardiovascular and ventilatory coupling to external work.

Specific applications

Exercise testing has wide applications in health and disease. This section proffers several ways in which exercise testing may be employed, including assessment of physical fitness, evaluation of exercise intolerance, diagnosis of disease, exercise prescription both in sports and clinical rehabilitation, and evaluation of therapeutic interventions. These broad categories, along with more specific applications of exercise testing, are listed in Table 1.3.

Assessment of physical fitness

Aerobic performance is one of the essential elements of physical fitness, along with muscle strength, flexibility, and body composition. Aerobic performance is defined by certain parameters that can be measured using carefully selected exercise-testing protocols. The best known of these parameters is maximum oxygen uptake ($\dot{V}o_{2max}$). The

Table 1.2. Recognizable exercise response patterns which assist in exercise test interpretation

Normal response	Abnormal response
Maximal effort	Abnormal cardiovascular response pattern
Cardiovascular limitation	Impaired oxygen delivery
Suboptimal effort	Ventilatory limitation
	Abnormal ventilatory response pattern
	Abnormal ventilatory control
	Impaired gas exchange
	Abnormal muscle metabolism
	Abnormal symptom perception

other parameters are the metabolic threshold ($\dot{V}o_2\theta$), work efficiency (η), and the time constant for oxygen uptake kinetics ($\tau\dot{V}o_2$). Each of these parameters is described in detail in Chapter 4. They can be derived with accuracy provided the appropriate instrumentation and testing methods are used, as described in Chapters 2 and 3. Determination of one or more of the parameters of aerobic performance for a given individual facilitates the prescription of exercise based on meaningful physiological data. Furthermore, the identification of the important metabolic markers such as $\dot{V}o_{2max}$, $\dot{V}o_2\theta$ and the ventilatory threshold ($\dot{V}_E\theta$) defines the physiological domains of exercise intensity for a given individual. These domains can in turn be used to prescribe an exercise program logically based on knowledge of the metabolic profile of that individual.

Exercise testing, with repeated determination of certain parameters, e.g., timed walking distance, $\dot{V}o_{2max}$ (directly measured or estimated), the relationship between f_C and $\dot{W}$, and $\dot{V}o_2\theta$ can be used to track individual progression in response to exercise training or a program of rehabilitation. Properly conducted field tests using appropriate instruments (see Chapter 2) generally provide reliable results. Field tests are valuable for progress monitoring, even though absolute accuracy may be less than desired. This latter point is particularly applicable to estimations of $\dot{V}o_{2max}$.

Evaluation of exercise intolerance

In the clinical laboratory specially designed exercise-testing protocols can be used to study the wide range of physiological variables during incremental exercise. Applied to a symptom-limited maximal exercise test, this approach facilitates the identification of specific physiological limitations for a given individual. Hence, when an individual complains of exercise intolerance, the physiological responses can be carefully examined to see if they offer a plausible explanation for the subject's symptoms.

A special application in the evaluation of exercise intolerance is disability evaluation. A successful disability claim often has important financial implications for the claimant. Thus, it needs to be supported by objective measures of exercise incapacity. The symptom-limited incremental exercise test identifies those with genuine exercise limitation, those who deliberately give a submaximal effort, and those who have normal exercise capacity despite their symptoms.

Differential diagnosis of disease

Cardiovascular diseases

One of the most valuable applications of clinical exercise testing is the ability to distinguish cardiovascular from pulmonary causes of exercise limitation. In the arena of clinical exercise testing, particularly with older subjects, cardiovascular and pulmonary diseases frequently coexist. The symptom-limited incremental exercise test helps identify which of these conditions is the limiting factor. This can have important implications in terms of the direction and goals of treatment.

A variety of incremental treadmill protocols have been used for the detection of myocardial ischemia due to coronary artery disease. These protocols are usually limited to measurement of heart rate, blood pressure, and a detailed recording of the electrocardiogram. The incremental exercise test can also identify early cardiovascular disease such as cardiomyopathy. However, it is often difficult to distinguish early cardiovascular disease from physical

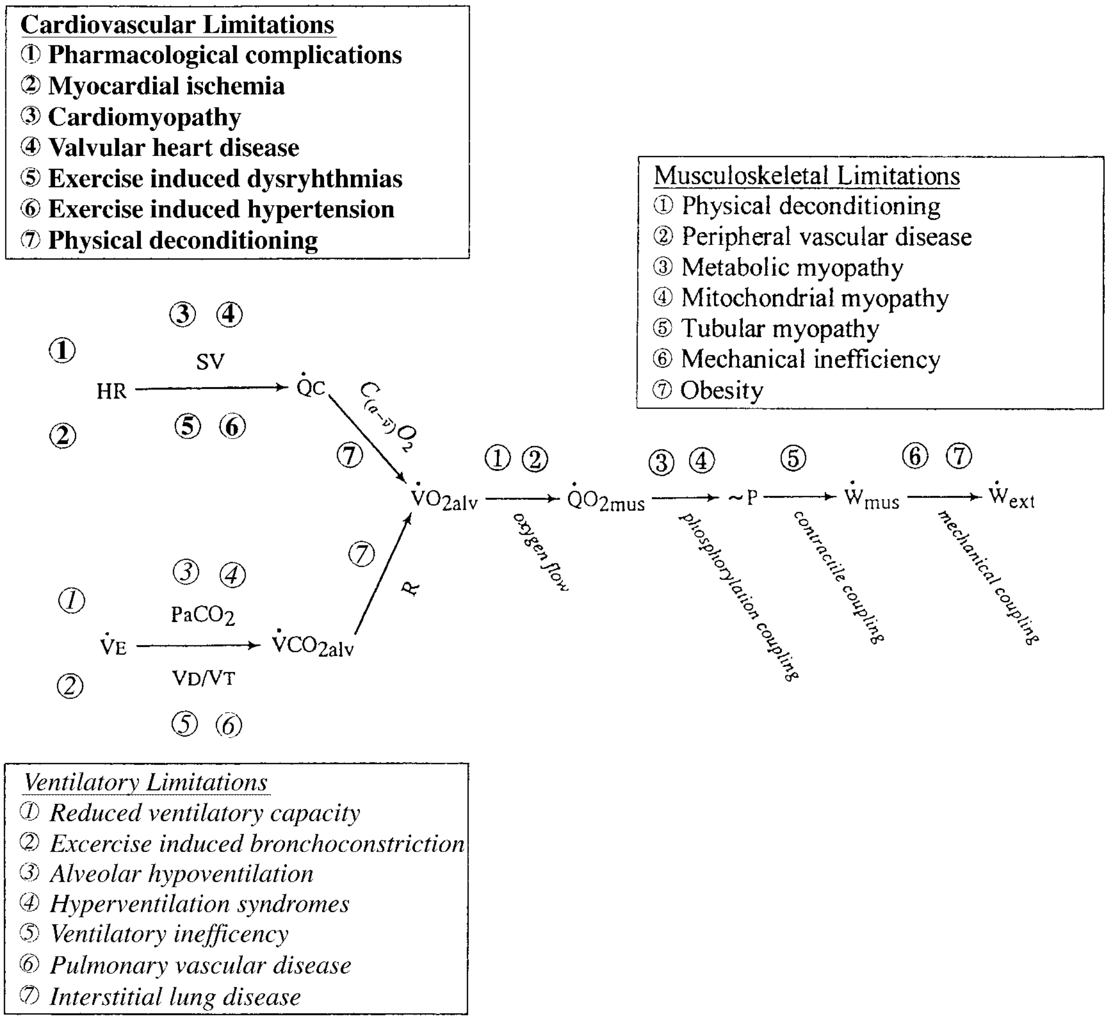

Figure 1.6 Cardiovascular, ventilatory, and musculoskeletal limitations which affect the performance of external work.

deconditioning. This dilemma will always exist in the field of exercise assessment because the physiological consequences of these two conditions are similar. The best way to resolve this dilemma is by using exercise prescription and repeated testing to reveal how much of the physiological abnormality is reversible.

Disorders of ventilation

Diseases of the lungs and respiratory muscles are usually characterized by pulmonary function testing as being either obstructive (e.g., asthma and chronic bronchitis) or restrictive (e.g., pulmonary fibrosis or respiratory muscle weakness). Unfortu-

Table 1.3. Specific applications of exercise testing

Specific applications of exercise testing
Assessment of physical fitness
Baseline fitness evaluation
Exercise training prescription
Demonstration of training response
Evaluation of exercise intolerance
Identification of specific physiological limitations
Disability evaluation
Differential diagnosis of disease
Cardiovascular diseases
Cardiomyopathy
Distinguishing cardiovascular from pulmonary disease
Screening for coronary artery disease
Disorders of ventilation
Obstructive pulmonary disease
Restrictive pulmonary disease
Hyperventilation syndrome
Disorders of pulmonary gas exchange
Interstitial lung disease
Pulmonary vascular disease
Diseases of muscle
Distinguishing myalgia from myopathy
Psychological disorders
Malingering
Anxiety
Secondary gain
Exercise prescription
Physical training
Clinical rehabilitation
Evaluation of other therapeutic interventions
Lifestyle modifications
Nutritional
Weight management
Smoking cessation
Pharmacological interventions
Ergogenic drugs
Oxygen therapy
Surgical interventions
Preoperative risk assessment
Coronary artery bypass grafting (CABG)
Valve replacement
Cardiac transplantation
Lung volume reduction surgery (LVRS)
Lung transplantation

nately, this categorization does not predict what physiological limitations or inefficiencies these types of disease impose during exercise. Symptom-limited incremental exercise testing reveals those individuals with true ventilatory limitation dictated by mechanical factors and those with abnormalities of ventilatory control. Furthermore, a detailed study of breathing pattern can be undertaken at various stages of exercise intensity.

Disorders of pulmonary gas exchange

Incremental exercise remains the best method for challenging the mechanisms of pulmonary gas exchange and detecting early interstitial lung disease. By the same token, sequential exercise testing offers the most accurate means of assessing progression of interstitial lung disease and the response to treatment. Physiological abnormalities can be detected at maximal exercise when resting pulmonary function tests and arterial blood gases are normal. A specific situation where knowledge of whether or not someone has abnormal pulmonary gas exchange is important is the person who might have interstitial lung disease from an occupational exposure (e.g., asbestos).

Diseases of muscle

Increasing numbers of patients complain of muscle soreness on exercise or one of the fatigue syndromes. Incremental exercise testing provides the means of determining whether exercise capacity is truly diminished, and again points to the specific physiological limitations. An exercise-testing laboratory can evaluate patients with myalgia to determine whether muscle biopsy is justifiable. When the pattern of the exercise response suggests myopathy, a muscle biopsy can be requested with special histochemical stains and electron microscopy. Thus, exercise testing finds a role in making the important distinction between myalgia and true myopathy.

Psychological disorders

A variety of psychological conditions present with exercise intolerance. Exercise capacity may be surprisingly normal. More commonly, exercise capacity is reduced. This may be due to simple deconditioning from inactivity. Alternatively, it may appear that the physiological responses to submaximal exercise are normal and that exercise capacity is consciously or subconsciously reduced for non-physiological reasons. Observation of the pattern of submaximal effort is particularly helpful in this type of evaluation.

Experienced exercise laboratory staff often find they have the ability to detect when an individual is not genuinely limited. Discreet inquiry can reveal that these individuals receive secondary gains from their apparent disability. Other psychological problems such as anxiety and hyperventilation are readily observed in the setting of the exercise laboratory. Laboratories should develop reliable methods for reporting these types of observation (e.g., using psychometric scales).

Exercise prescription

Apparently healthy individuals

Increasing numbers of healthy individuals seek an exercise prescription for the maintenance of physical fitness. Individuals training for competition demand more intensive physical training. In both of these situations, the exercise prescription is best developed on the basis of formal exercise testing.

Traditional approaches have relied upon estimates of maximum heart rate to determine a ‘‘training zone.’’ These methods, whilst unarguably effective to some extent, cannot be regarded as totally reliable. A preferred approach is to use exercise testing to define the metabolic domains of exercise intensity, which exist for a given individual. These domains can be anchored by heart rates or ratings of perceived exertion and linked to metabolic energy expenditure. Exercise programming can then be devised with a true scientific basis.

Given that baseline exercise testing is the most reliable method for establishing an exercise prescription, thereafter repeated exercise testing is necessary to document improvement in aerobic performance, or improved performance for a specific field event.

Table 1.4. Clinical exercise thresholds relevant to cardiac and pulmonary rehabilitation

Cardiac rehabilitation	Pulmonary rehabilitation
Metabolic (lactate)	Metabolic (lactate)
Myocardial ischemia (angina)	Hypoxemic (desaturation)
Hypertension	Dyspneic (breathlessness)
Hypotension	Tachypneic (anxiety)
Dysrhythmia	

Individuals with recognized illness

Exercise prescription is widely used in the discipline of rehabilitation, whether this is after musculoskeletal injury, myocardial infarction, or exacerbation of chronic pulmonary disease. Again, baseline exercise testing establishes an appropriate exercise prescription and repeated testing documents progress. In the cases of individuals with known cardiovascular or pulmonary diseases, specific thresholds need to be identified so that the exercise prescription can be delivered effectively within documented margins of safety.

Table 1.4 illustrates the important pathophysiological thresholds that may exist in individuals with recognized cardiovascular or pulmonary disease. Identification of these thresholds assists in developing a safe and effective exercise prescription for patients undergoing cardiac or pulmonary rehabilitation and is thus an important outcome of exercise testing. Importantly, individuals with cardiovascular and pulmonary diseases, even severe, should not be denied the potential benefits of regular exercise participation. Rather, they should be encouraged to exercise within safe limits to overcome the otherwise inevitable consequences of inactivity that would lead to physical deconditioning and contribute to a worsening of their overall health and quality of life. In this regard, exercise testing is a valuable asset.

Evaluation of other therapeutic interventions

Lifestyle modifications

Every year in the USA, 40 million individuals seek to reduce their body weight by nutritional or other means. Dietary adjustment alone is inappropriate without an exercise regimen. Therefore proper exercise prescription plays an essential role in weight management. Sequential exercise testing, either by simple field tests or with determination of oxygen uptake, documents the anticipated improvement in exercise capacity which in turn serves as positive feedback to the individual.

Another lifestyle modification which is important for many individuals is smoking cessation. Coupled with a carefully programmed exercise regimen, smoking cessation should lead to significant physical reconditioning and improvement in exercise capacity.

Pharmacological interventions

The sports industry has long been preoccupied with debate as to whether certain drugs have ergogenic properties, i.e. whether they themselves increase exercise capacity. Statements about the ergogenic capabilities of many drugs are exaggerated. However, the appropriate means of determining whether a drug itself is responsible for increased exercise capacity is to conduct field tests, maximal exercise tests, or comparison of key physiological variables for selected submaximal exercise protocols.

In the clinical arena, many pharmacological agents are prescribed with the intention, directly or indirectly, of improving exercise capacity and ability to perform the activities of daily living. These agents include drugs purported to improve skeletal muscle contractility, cardiac output, and ventilatory capacity or alternatively to reduce blood pressure, fatigue, breathlessness, or other limiting symptoms. Exercise testing is necessary to demonstrate objective evidence of such improvements.

Surgical interventions

Several studies have attested to the usefulness of exercise testing in preoperative risk assessment, particularly in patients with moderate and severe cardiac or pulmonary disease. In the past, many surgeons relied on intuition or a simple exercise challenge like stair climbing to assess physical fitness before surgery. Often their judgments were accurate, although not necessarily based on objective measures. In the modern era, with the availability of a range of formal exercise tests, actual determination of exercise capacity is appropriate. Maximum oxygen uptake and also the metabolic threshold of lactate accumulation have been shown to have discriminatory value.

Exercise testing has been used to assess patients awaiting heart and lung transplantation. The information which formal testing provides has been successfully used to prescribe rehabilitative exercise and obtain surprising improvements in exercise capacity in these groups of patients. Indeed, the rehabilitative improvements in some cardiac patients have been sufficient to obviate the need for transplantation. A similar approach might be considered before other types of cardiac surgery.

A surgical approach is now advocated for certain patients with severe emphysema. One of the major claims of so-called lung volume reduction surgery is improvement in exercise capacity. Indeed, this should be a primary goal if such surgery is to become widely accepted. Consequently, this type of intervention needs to be evaluated by formal exercise testing before and after surgery.

Conclusion

The ability to perform exercise is one of the most fundamental aspects of human existence. The ability to test exercise performance is therefore of utmost importance whether a subject desires athletic performance, exercise prescription, diagnosis of exercise limitation, or evaluation of a therapeutic intervention. This book attempts to bring a level of sophistication to exercise testing and interpretation that, if embraced, can greatly enhance the expertise of exercise professionals and increase the value of the information they provide.

FURTHER READING

Åstrand, P.-O. & Rodahl, K. (1986). *Textbook of Work Physiology. Physiological Bases of Exercise*, 3rd edn. New York: McGraw-Hill.

2

Instrumentation

Introduction

Before exercise tolerance is evaluated, the practitioner must carefully consider a number of factors that will ultimately influence the interpretation of results and ensuing interventions. These include the purpose of the test (Chapter 1), key variables required for accurate test interpretation (Chapter 4), and the best test available for the test objectives (Chapter 3). In considering which data will best serve these objectives, the practitioner should select the most appropriate instrumentation available for their collection. This chapter presents a number of instrumentation options in the context of test purposes and data desired for interpretation. These include relatively simple field tests, submaximal laboratory tests, and maximal effort tests. Details of actual application of these instruments will be presented in Chapter 3. Each instrument will be presented with its description and principle of operation followed by methods of calibration, its accuracy, and precision. Maintenance of the instrument is also discussed. This chapter begins with a brief review of important measurement concepts that influence instrument selection. Figure 2.1 illustrates these concepts.

Measurement concepts

Validation

An instrument is thought to be valid if it accurately measures the variable(s) it is said to measure. For example, a heart rate meter is valid if it accurately represents the true value of the heart rate. It is prudent for the practitioner to ensure the accuracy of measurement instruments. This requires periodic validation studies in which the instrument in question is compared against a ‘‘gold standard’’ or reference method in its ability to measure the variable in question. Unfortunately, absolute accuracy can only be determined if one is absolutely certain of the true value. This may be impossible. Thus, one must decide how much deviation from the true value (error) is acceptable. This decision should be made prior to the purchase of any instrumentation.

Calibration

Calibration is a procedure in which an instrument is adjusted consequent to its measurement of values for a variable known to be true. For example, when a scale is being calibrated, known weights are placed on the scale that is then adjusted according to the scale’s reading. It is important that calibrations be performed over the expected range of measurement for the variable of interest. Generally, this requires multiple trials with different known values. Again, using the scale example, if a laboratory scale was to be used for children, it might be reasonable to ensure calibration over a range of 20–50 kg, whereas in a sports medicine setting, a range of 80–180 kg may be more appropriate. Instrumentation should be purchased in consideration of the range of expected measurements. Calibration is not validation.

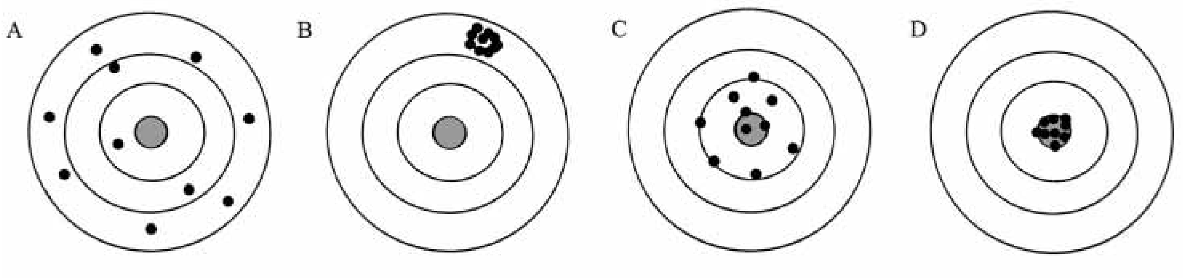

Figure 2.1 Illustrations of accuracy and precision using the analogy of shots fired at targets. (A) Poor precision and poor accuracy. (B) Good precision and poor accuracy. (C) Improved precision and improved accuracy. (D) Good precision and good accuracy.

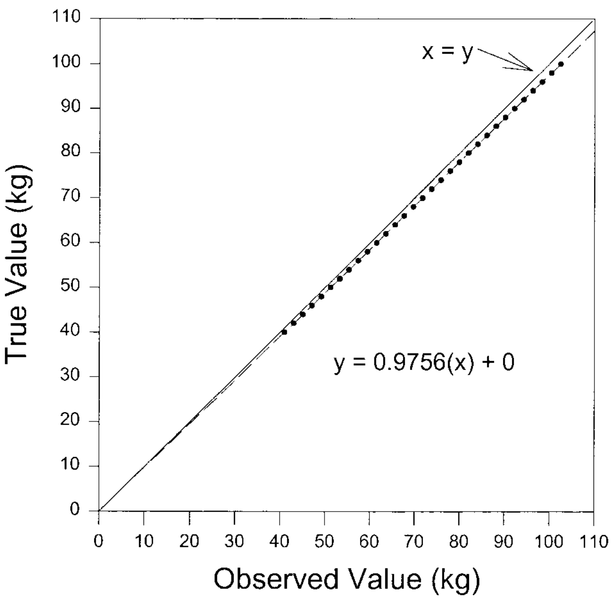

Figure 2.2 A calibration curve using the example of data obtained from the calibration of a laboratory scale. The true value for the measurement is plotted on the y-axis while the corresponding observed value is plotted on the x-axis. The regression equation is used to correct future measurements.

What to do with calibration data

In the event that the instrument cannot be physically adjusted to provide the true value, mathematical ''adjustments'' can be made in the form of a calibration curve. Suppose calibration is desired over the range of 40–100 kg, using the scale example suggested above. Known precision weights in 2-kg increments are set upon the scale and the observed value recorded from the scale's display. The true value (precision weight) is plotted against the observed value. A curve is then fitted to the data depending upon which model best fits the plotted data. A regression equation is obtained which is then applied to future observations. Figure 2.2 illustrates this method. Thus, if a subject is weighed on this scale with an observed value of 80 kg, applying the calibration curve would give the more accurate weight of $(80 \times 0.9756) + 0$ or 78 kg.

Accuracy

Accuracy refers to the ability of an instrument to measure its true value. If an instrument is accurate it is also said to be valid and reliable (or precise). For example if an oxygen analyzer reads a calibration gas certified to be 16.00% as 16.00%, it is accurate for that value. The oxygen analyzer (or, by extension, any other instrument) may not be accurate at another value. Instruments should have the capability of acceptable accuracy over the range of values one expects to measure.

Precision

Precision (reliability) indicates the ability of an instrument to yield the same measurement for a variable when that variable is measured repeatedly over time. Precision does not necessarily infer accuracy.