FUNDAMENTALS OF EXERCISE TESTING
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WORLD HEALTH ORGANIZATION
GENEVA
1971
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Preface

In an age when cardiovascular diseases are among the leading causes of death, procedures for assessing the functional efficiency of the heart and circulation are obviously of paramount importance to the medical profession. Exercise tests are widely used for this purpose and a great many articles and monographs have been published on exercise physiology and its cardiovascular implications. Unfortunately, this information is scattered in specialized literature and is not always easy to retrieve. This probably partly explains why no general agreement has been reached on how to perform exercise tests and how to interpret the results.

A great variety of tests are in use and each has its advocates. Some are relatively cheap and easy to perform but are unsuitable for taking complicated measurements and do not yield such reliable results as more elaborate tests. Hence there is a need to collect and summarize the scattered information on exercise tests, to collate data from sports medicine with those from clinical departments, and to standardize the various testing procedures in order to facilitate comparisons of investigations in different places and on persons of different ages, sex, and state of health.

The aim of the present book is to describe only the more widely used exercise tests for assessment of cardiovascular function and to advise on the interpretation of the results with a view to their practical application. Only the so-called “submaximum” tests that can be used in clinical practice and in routine surveys of population and occupational groups are described. The more strenuous “maximum” tests, which are especially of interest for basic research on exercise physiology and in assessing fitness for athletic performances, are not considered. Attention is, however, given to the applications of exercise tests in growth studies in children, in population studies, and in assessing suitability for specific jobs.

This book is not addressed to the specialist in exercise physiology, who would probably find it too elementary and limited in scope. On the other hand, it should not be considered a “do-it-yourself” instruction manual: the techniques described should be carried out only by persons who have already undergone a basic training in exercise testing in a specialized laboratory. It is hoped, however, that the book will provide useful guidance to cardiologists, epidemiologists, general practitioners, public health workers and paramedical staff interested in cardiovascular diseases and the assessment of physical fitness, suitability for jobs, and related problems.
Man, like most other animals, has the ability to move in relation to his environment and to perform various types of mechanical work by moving the different parts of his body. Such ability depends on the activity of the skeletal muscles, which are able to transform chemically stored energy into mechanical work during their contractions. Exercise performance engages the muscles in either static or dynamic work. All daily-life activities are maintained by various combinations of these two types of muscular work or by continuous shifts from one type to the other. In static effort, the maximum tension that can be produced by a given muscle group and the length of time it can be maintained (endurance) depend on the local functional capacity of the muscle, whereas in dynamic work the endurance and maximal power output depend on the efficiency of the energy-delivering mechanisms and their interactions with other body functions.

From a functional point of view, the total mass of skeletal muscles may be considered as an organ system, making up about 40% of the weight of the human body. Maintenance of posture and most daily activities involve only a small fraction of the muscular system, but vigorous activities related to heavy labour, sports and recreation require the integrated activity of nearly all the muscles. These seldom operate at maximum level at the same time: their activity pattern changes continuously as the individual muscles are called into play or are released under the control of the central nervous system.

At rest, the metabolic rate of the muscle tissue is low, demanding about 3 ml/min of oxygen per 100 ml of tissue, but during maximum dynamic activity the metabolic rate increases to 100 times the resting value. To cover the energy demand of the large muscle masses during strenuous effort, an ability to increase greatly the supply of oxygen is thus necessary. The oxygen-transporting system, which comprises the cardiovascular system (central and peripheral), the lungs and the blood, is constructed with such functional dimensions that it can meet the demand of the muscles, even where these are under maximum effort.
The Oxygen-transporting System in Exercise

Heart rate

The resting heart rate depends on a number of factors, including age, sex, position, fitness and environmental conditions. It is higher in the standing than in the supine position (Table 1) and it decreases with age. Physical training also reduces heart rate at rest, although the mechanism is so far unknown.

<table>
<thead>
<tr>
<th>Function</th>
<th>Rest</th>
<th>Moderate exercise</th>
<th>Maximum exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Supine</td>
<td>Upright</td>
<td>Supine</td>
</tr>
<tr>
<td>Cardiac output (litres/min)</td>
<td>5.6</td>
<td>5.1</td>
<td>19</td>
</tr>
<tr>
<td>Stroke volume (ml)</td>
<td>60</td>
<td>65</td>
<td>116</td>
</tr>
<tr>
<td>Heart rate (beats/min)</td>
<td>120</td>
<td>130</td>
<td>165</td>
</tr>
<tr>
<td>Systemic systolic arterial pressure (mm Hg)</td>
<td>20</td>
<td>19</td>
<td>36</td>
</tr>
<tr>
<td>Pulmonary systolic arterial pressure (mm Hg)</td>
<td>70</td>
<td>64</td>
<td>92</td>
</tr>
<tr>
<td>Arteriovenous oxygen difference (ml/litre)</td>
<td>4190</td>
<td>1.270</td>
<td>485</td>
</tr>
<tr>
<td>Total peripheral resistance (dynes sec/cm$^5$)</td>
<td>6.3</td>
<td>7.8</td>
<td>29.7</td>
</tr>
<tr>
<td>Left ventricular work (kpm/min)</td>
<td>250</td>
<td>280</td>
<td>1750</td>
</tr>
<tr>
<td>Oxygen uptake (ml/min)</td>
<td>44</td>
<td>44</td>
<td>48</td>
</tr>
</tbody>
</table>

* Observations made on young sedentary adult men; approximate values based on data compiled from the literature.

Physical effort causes the heart rate to increase. Such increase is under nervous control, mainly through a reinforcement of the ortho-sympathetic discharge, and occurs in spite of the increased peripheral arterial pressure. Liberation of catecholamines from the adrenal medulla may also play some role in the increase of heart rate, whereas temperature and chemical changes that occur in the blood do not seem to play a significant role. The heart rate during exercise, like the resting heart rate, also decreases with age (Fig. 1). A direct, linear relationship exists between heart rate and level of physical effort, at least in the range 50-90% of maximum oxygen uptake. This relationship is widely employed in a number of exercise tests. However, there are considerable individual differences because the correlation varies with sex, age, and physical fitness: for the same heart rate oxygen uptake is higher in males than in females and it is also higher in younger and in fitter subjects (Fig. 2).

During light exercise the first increase in the heart rate may be exaggerated, but subsequently it diminishes to a lower level which is maintained
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throughout the period of exercise. However, during prolonged work and particularly if the load is heavy, there is a tendency for the heart rate to increase as exercise progresses (Fig. 3); this reflects in part the tendency for stroke volume to diminish in heavy work (see below), and in part such factors as rising body-temperature, increasing lactate accumulation, and impending exhaustion.

During maximum work the heart rate increases until a state of exhaustion is reached. The terminal heart rate recorded in this situation is considered as the maximum attainable heart rate.

The highest attainable heart rate during the performance of heavy muscular work depends upon age and state of training (see Fig. 1 and 2). At the age of 20 years the maximum heart rate is about 200, but is reduced to about 160 at the age of 64. Slightly lower values are observed in women.

The decrease in maximum heart rate with increasing age can be considered as a sign of the inevitable and general reduction of biological functions

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**Fig. 1**

**DECLINE OF MAXIMUM HEART RATE WITH AGE IN HEALTHY MEN**

*From Fox et al. (1969). Data from studies of North American and European males under varying conditions and with differing criteria for those considered acceptably close to "maximum". The vertical lines give the spread of one standard deviation. The numbered horizontal lines are the "target" heart rate levels for stress testing in each decade as proposed by the Scandinavian Committee on ECG Classification and listed on p. 45.*
FIG. 2
HEART RATE DURING SUBMAXIMUM AND MAXIMUM EXERCISE IN YOUNG ADULT (20-30 YEARS) MEN AND WOMEN, SHOWING SEX DIFFERENCES AND VARIATIONS BETWEEN FIT AND UNFIT SUBJECTS*

A. Sedentary (unfit) subjects. B. Athletic (fit) subjects.

*Based on Hermansen & Lange Andersen (1965).
with aging. However, the precise mechanism involved in this age-induced decrease in maximum heart rate is not understood.

Stroke volume

At rest and in the supine position, the stroke volume of an adult non-athletic man is about 90 ml, depending upon his body size. In the standing position, the stroke volume is lower (see Table I). The stroke volume of women is about 25% lower than that of men in both body positions. As a result of the greater venous return which occurs on transition from rest to exercise, the stroke volume increases rapidly under effort, reaching a level that is maintained constant during an exercise of 5-10 minutes' duration, but decreases slightly if the exercise is prolonged.

Cardiac output

Cardiac output is a function of stroke volume and heart rate ($\dot{Q} = Q_s \times f_h$), which in turn depend on two fundamental characteristics of the heart muscle—namely, its contractility and its automatism—and can be modified by hormonal and neural influences.
The resting cardiac output depends upon body position because gravity exerts a marked effect upon the circulation. When the body changes from horizontal to upright, there is a tendency for blood to pool in the lower extremities; the central blood volume and the venous return decrease, and as a result the stroke volume and cardiac output are reduced (see Table 1). The resting cardiac output is a highly variable function, inasmuch as it is also greatly influenced by sex, age, environmental conditions, and emotional disturbances. It is necessary to take account of all of these factors in the analysis of cardiac function at work, but their importance becomes less as the intensity of exercise is increased. When a subject is lying down under basal conditions, the cardiac output is at a "steady state" level of about 5-6 litres/min (or if expressed on the basis of surface area, 3-3.5 litres/min/m²).

During the first few minutes of rhythmic dynamic muscular work¹ the cardiac output increases, first rapidly and then more gradually, to a new "steady state" level, which is a function of the intensity of work (Fig. 4). The new steady state level is reached at about the same time as the oxygen uptake levels off at its own steady exercise value.

**Fig. 4**

**ADAPTATION OF CARDIAC OUTPUT TO EXERCISE ON TREADMILL**

\[
\begin{align*}
Q & \text{ (litres/min)} \\
\text{TIME (min)} & \\
0 & \\
1 & \\
2 & \\
3 & \\
4 & \\
5 & \\
6 & \\
7 & \\
8 & \\
9 & \\
\end{align*}
\]

Intensity of exercise, with 5% slope:
- ● 3.2 km/h
- x 4.9 km/h
- ▲ 6.8 km/h

*Redrawn from Cerretelli et al. (1966).*

In spite of the tendency of stroke volume to decrease during prolonged exercise, cardiac output remains constant on account of the increased heart rate. Similarly, the higher maximum cardiac output and maximum oxygen uptake achieved in young as compared with old subjects is also due to a

¹ The response to isometric work is radically different. However, it will not be discussed here, being beyond the scope of this manual.
higher maximum heart rate in the young subjects. After cessation of exercise, cardiac output does not promptly return to the previous resting level, but decreases gradually following a somewhat exponential curve (Fig. 4).

**Pulmonary function**

The pulmonary ventilation of a resting adult man is 5-7 litres/min, but during muscular exercise hyperventilation develops parallel with the increase in oxygen consumption. In brief maximum exercise, fit subjects may reach values well above 100 litres/min, i.e., 20-25 times the resting level. The raised ventilation is a result of increases in both respiratory frequency and tidal volume. Rates of 40-50 breaths/min are observed in heavy exercise, and the tidal volume may reach 50% of the vital capacity.

The total lung capacity does not change much during exercise although it may decrease slightly as a result of the increased intrathoracic blood volume. The tidal volume increases from 10-15% to about 50% of the vital capacity, mainly at the expense of the inspiratory reserve volume, which is correspondingly reduced (Fig. 5). The expiratory reserve volume, however, changes little, even at the highest level of exercise. The vital capacity tends to decrease in exercise since residual volume is increased, while the functional residual capacity may remain practically unchanged. This has some physiological significance: the oscillations of the air volume in the lungs are, obviously, much larger in exercise than at rest, and the maintenance of a

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large functional residual capacity thus assists in damping the pressure changes and holds the fluctuations of alveolar CO$_2$ tension to a tolerable level.

Pulmonary ventilation is closely related to CO$_2$ production. It increases in linear relationship with the increase in metabolism except in heavy exercise, when it increases disproportionately. Such disproportionate hyperventilation is due to anaerobiosis of the working muscle, and contributes an extra drive to the respiratory centre. The causes of such a drive are most likely the H$^+$ concentration in the blood and/or the CO$_2$ released as a consequence of the high blood lactate level.

Neural theories have been proposed to explain the regulation of respiration during exercise. Such theories involve either conditioned reflexes or irradiation of impulses from the motor centres at the same time as neuromuscular transmission, and would explain why ventilation sometimes increases even before the muscular effort begins. It is also possible that different factors play a role at different times: peripheral reflexes act at the beginning of exercise whereas chemical and thermal factors take over later to maintain hyperventilation during exercise.

The mechanism of hyperventilation during effort is still unknown. It is known, however, that exercise-induced hyperventilation is always of a lesser degree than the maximum voluntary ventilation and that respiration is not the main limiting factor in muscular exercise.

**Blood pressure**

(a) **Systemic circulation**

Despite an immediate and drastic dilatation of the resistance vessels of the working muscles on transition from rest to exercise, the systemic arterial pressure is not only maintained, but actually increases.

The initial period of increasing arterial pressure during performance of rhythmic exercise lasts 1-2 minutes, after which a fairly constant value is reached and maintained, the level depending upon the intensity of exercise. When work is stopped there is an immediate pressure drop to below previous resting values, the minimum being reached 5-10 seconds after cessation of work. The extent of the fall in pressure depends partly on posture, partly on room temperature and the duration of exercise, and partly on whether exercise is stopped suddenly or is tapered off. Subsequently, arterial pressure rises to a little above the pre-exercise level.

The systolic pressure taken at the apparently steady state level is roughly proportional to the intensity of work, and in maximum exercise it may reach levels well above 200 mm Hg (Table 1 and Fig. 6).

The diastolic systemic pressure remains practically unchanged in light and moderate exercise, but may increase slightly during heavy exercise. As a consequence of the differential rise in systolic and diastolic pressure, the pulse pressure increases greatly.
The type of effort also influences the rise in arterial pressure: an effort performed with the legs increases the arterial pressure to a lesser extent than the same effort performed with the arms. Static effort entails a considerable arterial hypertension, while heart rate and cardiac output increase only slightly.

The total resistance falls considerably during work, especially in transition from rest to light exercise (see Table 1). This fall is due to the drastic vasodilatation that occurs in the working muscles and also in the skin as exercise progresses.

Venous return to the heart during exercise is usually assured by muscular contraction, by intrathoracic "negative" pressure, and by modifications in the tonus of the walls of the capacitance vessels.

(b) Pulmonary circulation

Because of their anatomical structure and their intrathoracic localization, pulmonary vessels have a low resistance to blood flow and are highly compliant. They can therefore accept a several-fold increase of
cardiac output with only slight increase in pressure, at least during moderate effort. However, under heavy effort the limits of vascular compliance are approached and the pulmonary arterial pressure may increase markedly.

At rest and in the upright position the systolic pressure in the pulmonary arteries is 15-20 mm Hg, the diastolic pressure is 5-8 mm Hg, and the mean pressure is 8-12 mm Hg. In the supine position the pressures are somewhat higher.

During moderate work the pulmonary arterial pressure increases (see Table 1) in relation to the increase in cardiac output and heart rate (Fig. 7).

**FIG. 7**

**MEAN VALUES OF PRESSURE IN PULMONARY ARTERY AT REST AND DURING BICYCLE EXERCISE IN SUPINE POSITION**

![Graph showing mean pressures in pulmonary artery at rest and during exercise.](image)

*Athletes.

*Non-athletes.

*Redrawn from Bevegard et al. (1963).

**Blood flow**

During exercise, the body attempts to increase blood flow to the muscles to cover the increased metabolic needs, and the blood flow may rise to 20 times the resting level. Regulation of body-temperature puts an additional strain on the circulatory system during exercise, because the extra heat produced by the contracting muscles must be carried to the body surface. Consequently, muscular exercise involves a drastic adjustment of the circulatory function, with an increased total cardiac output and fine regulation of regional blood flow.
In addition to the increased cardiac output and the greater force exerted by the cardiac muscle resulting in higher mean systemic pressures, a redistribution of cardiac output occurs during exercise. Changes in organ blood flow are exemplified in Table 2.

<table>
<thead>
<tr>
<th>Circulation</th>
<th>Rest (ml/min; %)</th>
<th>Exercise (ml/min; %)</th>
<th>Light</th>
<th>Moderate</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Splanchnic</td>
<td>1 400; 24</td>
<td>1 100; 12</td>
<td>600; 3</td>
<td>300; 1</td>
<td></td>
</tr>
<tr>
<td>Renal</td>
<td>1 100; 19</td>
<td>900; 10</td>
<td>600; 3</td>
<td>250; 1</td>
<td></td>
</tr>
<tr>
<td>Cerebral</td>
<td>750; 13</td>
<td>750; 8</td>
<td>750; 4</td>
<td>750; 3</td>
<td></td>
</tr>
<tr>
<td>Coronary</td>
<td>250; 4</td>
<td>350; 4</td>
<td>750; 4</td>
<td>1 000; 4</td>
<td></td>
</tr>
<tr>
<td>Skeletal muscle</td>
<td>1 200; 21</td>
<td>4 500; 47</td>
<td>12 500; 71</td>
<td>22 000; 88</td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>600; 9</td>
<td>1 500; 15</td>
<td>1 900; 12</td>
<td>600; 2</td>
<td></td>
</tr>
<tr>
<td>Other organs</td>
<td>600; 10</td>
<td>400; 4</td>
<td>400; 3</td>
<td>100; 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 800; 100</td>
<td>9 500; 100</td>
<td>17 500; 100</td>
<td>25 000; 100</td>
<td></td>
</tr>
</tbody>
</table>

* Estimated figures; taken from Lange Andersen (1968).

(a) Muscle blood flow

Blood flows through the resting muscle at the rate of 4-7 ml/min/100 ml of tissue. During strenuous rhythmic contractions the flow increases greatly, reaching rates of more than 100 ml/min/100 ml of tissue, or 15-20 times the resting value. The number of open capillaries in the working muscle may be up to 50 times the number in the muscle at rest.

The blood flow increases at the onset of exercise or even in anticipation of exertion, and it continues to increase until a plateau—a steady state between inflow and outflow—is reached. This period of adaptation usually takes one to two minutes in light or moderately heavy exercise, but is possibly longer in maximal exercise. The steady state level is closely related to the intensity of work performed and to the aerobic metabolic activity of the tissue. After cessation of work the blood flow gradually decreases in relation to the restoration of normal tissue homoeostasis.

The increase of muscle blood flow during exertion is made possible in part by the constriction of the resistance vessels of the muscles that are still at rest. During exercise there is indeed an increase of vasoconstrictor tone in the muscles not involved in the effort: for example, in the forearm muscles the blood flow decreases slightly during leg exercises.

Although the rate of blood flow in the muscle during exercise increases only 15-20 times above the resting value, the aerobic metabolism for muscle fibres may increase up to 100 times. This implies a greater extraction of oxygen from the blood passing through the tissue. While normal utilization of oxygen amounts to only 20-25% in most organs, the muscle is indeed capable of extracting more than 80% of the oxygen offered to it by the
blood so that the oxygen tension of the blood flowing out of the active muscles may be close to zero.

(b) Coronary blood flow

The rate of blood flow to the cardiac muscle increases during muscular exercise and is linearly related to the increase in cardiac output. The rate of blood flow to the cardiac muscle at rest is about 60-70 ml/min/100 ml of tissue, and it may increase at least fivefold during exercise. The oxygen extraction in the myocardium is very high even at rest (70-80%). Thus, any increased demand for oxygen must be met by an increased coronary blood flow. Accurate regulation of the coronary flow is important inasmuch as the cardiac muscle cannot utilize anaerobic glycogenolysis as a source of energy.

The resistance vessels of the myocardium have sympathetic innervation, but it is by no means agreed how important the autonomic nerves are to normal flow regulation. Contrary to their action in many other tissues, the catecholamines cause a vasodilatation of the myocardium's resistance vessels. It seems established, however, that the nervous vasomotor control of the coronary blood flow plays a minor role in the regulation of the intracardial circulation. The control mechanism is that of an autoregulation, and two factors are mainly responsible for setting the rate of coronary blood flow: the rate of myocardial metabolism and the pressure in the aorta.

(c) Pulmonary blood flow

During exercise in the upright position, which may increase the cardiac output up to 4-5 times that of the resting level, the blood in the lungs flows through more capillaries, and, because of the rise in arterial pressure, perfusion of the upper zones is improved. The cross-sectional area of the capillary bed of the lungs increases by a factor of 2-3 during maximal exercise. This means that the velocity of blood flow through the capillaries increases during work. It has been estimated that, at rest, a red blood cell remains in the pulmonary capillaries for 0.75 second, while in heavy exercise the time is reduced to 0.3 second.

The pulmonary capillary bed at rest contains about 70-100 ml blood, an amount that may be doubled during performance of heavy exercise. The blood content of the total pulmonary circuit ranges between 350 ml and 800 ml at rest, and rises to 1400 ml or more in exercise.

(d) Blood flow in visceral organs

In a normal resting man with a cardiac output of 5 litres/min the visceral organs (kidneys, liver, spleen and gastrointestinal tract) receive about 2.5 litres/min or 50% of the cardiac output.

During muscular exercise both the resistance and the capacitance vessels of the visceral organs constrict greatly, so that the blood flow to these organs
decreases and the volume of blood in the splanchnic area is reduced. The kidneys suffer the most drastic reduction of blood flow. At rest, renal blood flow is about 1100 ml/min, or about 20% of the cardiac output (Table 2), but during exercise the absolute renal blood flow is reduced by 50-80%. This decrease is roughly related to the intensity of effort and, indeed, zero values for kidney blood flow have been obtained occasionally during short spells of heavy exercise.

A large share of the resting cardiac output flows through the vessels supplying the intestines and the spleen, whence it is directed to the portal venous system; 100 ml/min circulate through this system at rest. The portal system plus the arterial blood to the liver constitute the splanchnic circulation whose blood flow at rest is about 1400 ml/min, i.e., about 24% of the cardiac output (Table 2).

It seems a general principle that the degree of vasoconstriction of the visceral organs induced by muscular exercise is related both to the relative intensity of work and to the circulatory requirements of heat dissipation.

(e) Skin blood flow

Circulation through the skin has two major functions: to provide transportation of metabolic material to the tissue and to conduct heat from inside the body to the surface for exchange with the environment.

The rate of blood flow through the skin is highly variable. The flow required depends on the cooling power of the surrounding air and the overall metabolic rate of the body, but excitement and emotional disturbances may also lead to marked variations in skin blood flow.

Under ordinary conditions the total blood flow to the skin is about 500 ml/min in the average adult man. On passing from rest to exercise blood flow through the skin decreases, but continuous exercise results in subsequent vasodilatation and increased flow (Table 2). When the skin vessels are fully dilated, such as during exercise, they may conduct up to seven times as much blood as when at rest, i.e., 3 litres/min, or about 15% of the cardiac output.

Blood gases and pH during exercise; haematocrit

The increased pulmonary ventilation during exercise secures a normal or increased oxygen tension in the alveoli. The oxygen tension in arterial blood does not change much at submaximum exercise, but at very high work rates a small decrease may be observed. The P\textsubscript{CO\textsubscript{2}} and the alkaline reserve determine the pH of the arterial blood; this is about 7.4 for a man at rest under ordinary conditions. Blood pH is unaffected by exercise as long as P\textsubscript{CO\textsubscript{2}} and the alkaline reserve remain unchanged. The arterial P\textsubscript{CO\textsubscript{2}} changes only slightly during exercise in a normal subject, at least during moderate work. Marked changes occur, however, during heavy work.
When anaerobiosis occurs in muscles (to supplement the aerobic processes in providing energy for muscle contraction), lactic acid is formed and the pH of the blood decreases. In exercises of up to 10 minutes' duration this takes place at work rates higher than 50-60% of the maximum aerobic capacity, depending on the physical fitness of the subject and on the type of exercise performed (Fig. 8).

During brief periods of exercise the haematocrit values also increase (see Table 1) in rough relation to the intensity of work. Such haemoconcentration, due to loss of plasma volume, occurs over the first few minutes and may amount to as much as 20%. During prolonged work there seems to be no further change.

The haemoconcentration entails some functional consequences. The oxygen-carrying capacity of the blood is raised owing to the increased concentration of red blood corpuscles. The acid-buffering capacity of the blood is also increased, owing to the increased concentration of plasma proteins. These adjustments are beneficial in exercise. On the other hand, haemoconcentration also increases the viscosity of the blood, thus hampering the
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blood flow. Clotting time and white cell count are also changed by the haemoconcentration.

Energy Requirements and Oxygen Uptake during Exercise

The energy requirement of the resting man is approximately 1.25 cal/min (or 0.25 litre/min of oxygen (see Table 1); this figure varies somewhat with body-size, age, sex and environmental factors. During muscular exercise the energy requirement may increase 15- to 20-fold. The energy cost of work is conveniently determined by indirect calorimetry, which involves determination of oxygen uptake ($V_O_2$).

When rhythmic dynamic muscular exercise is performed at a steady sub-maximum rate on a bicycle ergometer or similar instrument, oxygen uptake increases during the first few minutes of exercise and then reaches a plateau, the so-called "steady state" level. Regardless of the intensity of effort, an oxygen deficit is established at the beginning of exercise (adaptation phase or "on-transient") and remains throughout the whole exercise period: this oxygen debt is repaid after the cessation of exercise (recovery phase or "off-transient") (Fig. 9). During the recovery period, oxygen uptake and CO$_2$ production gradually decrease to resting levels following either a single exponential curve, if the work-load has been light and did not result in excess lactate formation, or a two-component exponential curve if the exercise was heavy. The length of both the adaptation and the recovery phase is a function of the intensity of exercise, of age, of sex and of the state of physical training (Lange Andersen, 1959).

![Figure 9](image)

**FIG. 9**
OXYGEN UPTAKE IN RELATION TO PERFORMANCE OF MODERATE (70 kpm/min) MUSCULAR EXERCISE ON A BICYCLE ERGOMETER*

*Figure kindly supplied by Professor K. Lange Andersen.

In light and moderate work the duration of the "on-transient" is one to two minutes; fit subjects adapt to exercise more quickly than unfit or older subjects, in which the adaptation phase may occupy several minutes. This
lag in circulatory adjustment causes partly anaerobic conditions in the muscles at the beginning of work and results in an oxygen deficit.

When steady state oxygen uptake is plotted against the rate of work performed, e.g., on a bicycle ergometer, the oxygen cost of exercise is seen to be linearly related to the rate of work up to a limiting value, above which a further increase of work load does not bring about any further increase in oxygen uptake. This level of $O_2$ consumption is defined as the maximum oxygen uptake, $(\dot{V}_O_2)_{\text{max}}$, for a particular type of exercise.\(^1\)

**Maximum aerobic power and maximum oxygen uptake**

Maximum aerobic power is defined as the highest attainable rate of aerobic metabolism during the performance of rhythmic dynamic muscular work that exhausts the subject within 5-10 minutes. It depends on the type of exercise performed, on the mass of muscles employed in the activity, and on various physiological variables. The highest values are obtained in activities like running, stepping, and bicycling, with only small differences between them. Large enough muscle groups are brought into play during these activities for the oxygen-transporting system to be loaded to, or close to, its maximum capacity.

Maximum aerobic power is assessed through the measurement of the maximum oxygen uptake attained in dynamic muscular exercise (see Chapter 8, page 76).

Oxygen uptake depends upon the muscle mass and the functional dimensions of the oxygen-transporting system, including such factors as respiratory and cardiac efficiency, the oxygen-transporting capacity of the blood, alveolocapillary diffusion, peripheral circulation, capillary-to-cell diffusion, and tissue diffusion.

Maximum oxygen uptake is related to the heart rate, stroke volume, and arteriovenous oxygen difference through the equation:

$$ (\dot{V}_O_2)_{\text{max}} = f_h \times Q_s \times (C_{a,o_2} - C_{v,o_2}) $$

The maximum oxygen uptake and, consequently, the maximum aerobic power of an individual are mainly determined by his age, sex, and body constitution, but a number of racial and environmental factors, and also pathological disturbances, are known to modify this parameter (Lange Andersen, 1968; Shephard, 1969).

Age exerts a considerable influence on maximum oxygen uptake (Fig. 10), an influence that has been established in a number of populations. The course of age-related changes is also affected by cultural attitudes to activity.

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1 Some authors make a distinction between "maximum" and "hypermaximum" work, on the basis that the maximum work rate corresponds to maximum oxygen consumption, and additional work is performed anaerobically. However, this distinction is not universally accepted.
In early childhood there are no sex differences in (\(\dot{V}_O_2\))_{max}, but at the onset of adolescence sex differences do appear and result in higher values for boys (see also Table 7 (page 108) and Table 8 (page 109).

Maximum oxygen uptake increases during childhood at approximately the same rate as weight and height, and in male subjects it reaches peak values during early adulthood. A gradual and steady decline with age takes place from 25-30 years and at the age of 70 maximum aerobic power is about 50% of that found at 20 years. In women the peak value—about 70% of that of men—is reached at the end of adolescence and remains fairly constant during the fertile part of life, declining thereafter at about the same rate as in men.

Maximum oxygen uptake is directly related to body weight (Åstrand, 1952; Lange Andersen, 1966) and it is therefore common to express it in ml/min/kg body-wt. It is also directly related to height and some authors favour this way of expression. When assessing the cardiovascular performance of obese people it is questionable whether maximum oxygen uptake should be expressed per kg of body weight; this penalizes the obese, but it may be a fair penalty since most forms of activity are weight dependent. Considerable evidence is available that maximum oxygen uptake deteriorates in certain
acute and chronic diseases. This deterioration may be a result of special pathological conditions, but is also due to physical inactivity, e.g., bed-rest.

When maximum oxygen uptake is reduced by acute disease or injury, it may be quickly restored to a normal value by an adequate rehabilitation regimen involving endurance exercises.

The measurement of maximum aerobic power has been introduced as a clinical routine programme to evaluate the functional status of the cardiovascular system (Wahlund, 1948; Sjöstrand, 1960; Reindell et al., 1967; Denolin, 1966; Chapman, 1966; Hellerstein & Hornsten, 1966; Fried & Shephard, 1968).

In clinical practice, reference standards for maximum oxygen uptake must be employed. The normality with regard to this parameter may be described by the mean ± two standard deviations previously established by studying samples of healthy people. As mentioned above, most laboratories express the maximum oxygen uptake in relation to body size (ml/min/kg body-wt or ml/min/cm body-ht).

It is also common to express it in relation to the volume of the heart as determined by X-ray technique (Reindell et al., 1967), or to total blood volume and total haemoglobin (Åstrand, 1952). The determination of maximum oxygen uptake is particularly relevant in the clinical testing of fitness for work and sport, in the diagnosis of the current status of the cardiovascular system, and in evaluating the effect of rehabilitation programmes.

As to the anaerobic components of muscular work, they are difficult to assess accurately and are also of less significance than the aerobic ones in relation to cardiovascular function and to the everyday activity of the average person.
CHAPTER 2

Types of Exercise Test

Different principles and various types of exercise have been employed in work tests. The objectives of the testing programme are:

1. to test the fitness for work, sport and other activities;
2. to evaluate the functional status of the cardiovascular (and/or respiratory) system in health and disease, including the diagnosis of present status, the prediction of the probability of developing cardiovascular disease, and the prognosis if the disease is already present; and
3. to evaluate the effect of preventive, therapeutic and rehabilitation programmes, including the effects of medication, surgery, physical conditioning, and other means of improving health.

In addition, fitness tests have been used to reassure patients and motivate them to improve their health. A recent evaluation of exercise testing procedures can be found in Parmley et al. (1969).

Determination of the circulatory and respiratory recovery time following completion of a standard work task has been widely used for studying fitness for work, and is based on the principle that quicker recovery means better fitness. For a given effort, the fitter the subject the lower his heart rate; conversely, for a given heart rate, the fitter the subject the more intense is the work he can perform. As early as 1889 it was observed that systolic blood pressure and heart rate rose during exercise and gradually returned to normal after exercise. In these early tests, blood pressure and pulse rate were measured after an exercise and were compared with the pre-exercise values. If these readings did not differ significantly the individual was considered to have a normal myocardial function.

Schematically, two main classes of tests may be recognized:

(a) Recovery tests (measurements are taken during the recovery period following exercise).

(b) Effort tests (measurements are taken during exercise).

It is now generally agreed that the most reliable information regarding effort tolerance is obtained from physiological observations made during
exercise. The main justification for the use of recovery tests in the past was the difficulty of measuring physiological functions during exercise. However, modern equipment has greatly facilitated such measurements and it is no longer a problem to obtain accurate values for metabolic, circulatory and respiratory functions during exercise.

Recovery Tests

In 1929, Master & Oppenheimer introduced a standard “two-step test” for the recording of blood pressure and heart rate responses to muscular exercise. Subsequently, the test was used as a work-load for post-exercise ECG recording (Master & Jaffé, 1941). In this test the load (in terms of rate and duration of stepping) is adjusted according to the age, sex, and body weight of the subject, and can be read off a table (Master & Rosenfeld, 1967); however, it is now widely recognized that the intensity of exercise required in this test is rather low and that the adjustments made for differences of body weight are too large.

In spite of these shortcomings, the Master two-step test is widely used Master & Rosenfeld (1967) summarized their experience and stated that the test was simple and reliable and aided in the discovery and evaluation of coronary heart disease and in the assessment of the coronary circulation during exercise in those subjects with other forms of heart disease.

Among other step tests currently in use is the Harvard test, which was introduced in the USA by Brouha et al. (1943). In this test the patient was required to step on and off a bench 51 cm (20 inches) high at a fixed rate (30/min) for five minutes or until exhausted. The heart rate was recorded three times (1-1½, 2-2½ and 4-4½ min) after cessation of work and was used together with the total performance time in the calculation of a fitness index. A pack-test version had previously been worked out by Johnson et al. (1942), mainly for the testing of military personnel; this test involved carrying a rucksack proportional in weight to the weight of the subject.

A simplified Harvard test has been introduced in Scandinavia (Ryhming, 1953); the height of the bench is 40 cm, and only one heart rate is counted in the recovery phase—namely, 1-1½ minutes after cessation of work. This count multiplied by two is termed the “test-pulse”. Reference standards for healthy males are available (Lange Andersen, 1955).

Effort Tests

So far as the intensity of effort is concerned, exercise tests may be classified as:

(a) Maximum tests (exercise of increasing intensity is performed until no further increase of oxygen uptake occurs);
(b) Submaximum tests (tests performed at lesser intensities of effort than the maximum tests).

As to the loading, three principal patterns are in use (Fig. 11):

**FIG. 11**

*TYPES OF LOAD USED IN EXERCISE TESTS*

<table>
<thead>
<tr>
<th>Single-level load</th>
<th>Continuous or almost continuous increase in load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discontinuous series of increasing loads with intermittent rest periods</td>
<td>Continuous series of increasing loads with an almost steady state at each level</td>
</tr>
</tbody>
</table>

*Each of these types of load may be applied in any of the following types of exercise: steps or bench, upright bicycle, supine bicycle, and treadmill. (Reproduced with slight modification from the report of a WHO Meeting on Exercise Tests in Relation to Cardiovascular Function, *WHO Hlth Org. techn. Rep. Ser.*, 1968, No. 388, p. 10.)*

**Single-level load**

Each individual performs exercise at a single constant level on a given day. The level is either kept the same for all subjects or is adjusted according to the health, age, sex, and physical fitness of the individual.

**Discontinuous series of increasing loads**

This type of test involves a series of exercises in which the load is increased in steps, between which short rest pauses are allowed.

**Continuous or almost continuous series of increasing loads**

In this type of test the work-load is increased in an almost continuous series of steps of variable short duration without rest pauses; the truly continuous increase of work-load is a special case of this procedure. An almost continuous increase of load can be achieved with some forms of bicycle ergometer and with the treadmill; it is also quite readily achieved in step tests, particularly if an electrical metronome is used to increase the subjects' pace.

In selecting the manner to apply the work-load, the following factors need to be considered:

(a) With a single work-load it is difficult to develop a test procedure which can be utilized in a population that is heterogeneous in respect of work capacity, since a single work-load does not exert a similar cardiovascular stress for even a relatively homogeneous sample with regard to age, sex, and
occupation. Also, a single work-load does not take into consideration the advisability of a warm-up period before performing exercise and may dangerously overstress a patient. Multi-stage tests, on the other hand, can satisfy these requirements but require more time.

(b) If a multi-stage procedure is to be used one needs to consider the advantages of intermittent versus continuous increase in work-load. With intermittent increases, there is the advantage of being able to obtain periodic measurements during rest. With this procedure, however, the testing time is substantially increased over the continuous method.
Procedures for exercise testing vary widely. The simplest and least standardized procedures involve knee-bending, flexing and extending the arms, hopping and jumping, climbing stairs, or walking or running a predetermined distance. More refined techniques are described below.

Proper exercise testing requires either the measurement of oxygen consumption or the performance of a measured amount of work by the subject. This implies for a step-test accurate measurement of the height climbed, and for a bicycle ergometer a simple and reproducible method of calibrating the instrument. It is also important that the test should be easily performed by the subject and that the rate of work performed can be set at any desirable level.

In addition to these basic requirements it is also essential, particularly when testing cardiovascular responses, that the mode of exercise selected should activate most of the larger muscles of the human body. Furthermore, it is desirable that the test procedure should not involve any muscle activity that requires special skill or co-ordination for its performance. A difficult and unfamiliar task may create anxiety and may lead to a discontinuous and uneven work rate, with a consequent bias in the value of the physiological parameters. In order to ensure co-operation, the exercise should preferably be enjoyable to the patient, and both the immediate exercise task and the general laboratory environment should not only be free from hazard but should also appear so to him.

Several types of ergometers are suitable for routine exercise testing:

(1) Bicycle ergometer (upright or supine);
(2) Steps;
(3) Treadmill;
(4) Arm crank.

Each of these has its merits and disadvantages, and the type of work task selected for a specific study depends upon its purpose and the nature of the population sample. The relative merits of the first three ergometers are summarized in Table 3.
**TABLE 3. RELATIVE MERITS OF EXERCISE TESTS**

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Type of test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Step</td>
</tr>
<tr>
<td>A. Ease of Performance</td>
<td></td>
</tr>
<tr>
<td>Familiarity with task required?</td>
<td>+ + +</td>
</tr>
<tr>
<td>Ease of obtaining high oxygen uptake</td>
<td>+ +</td>
</tr>
<tr>
<td>Subject's performance to maximum oxygen uptake</td>
<td>+</td>
</tr>
<tr>
<td>Ease of instrument calibration</td>
<td>+ +&lt;sup&gt;g&lt;/sup&gt;</td>
</tr>
<tr>
<td>Ease of measuring applied power</td>
<td>+ +&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td>Ease of recording or obtaining the following during maximum test:</td>
<td></td>
</tr>
<tr>
<td>ECG</td>
<td>±</td>
</tr>
<tr>
<td>Blood pressure</td>
<td>±</td>
</tr>
<tr>
<td>Blood samples</td>
<td>- -</td>
</tr>
<tr>
<td>Respiratory volume and oxygen</td>
<td>- -</td>
</tr>
<tr>
<td>Need for providing for emergency care&lt;sup&gt;h&lt;/sup&gt;</td>
<td>+</td>
</tr>
<tr>
<td>Ease of breathing</td>
<td>+ + +</td>
</tr>
<tr>
<td>Ease of obtaining a nearly continuous increase of effort&lt;sup&gt;i&lt;/sup&gt;</td>
<td>±</td>
</tr>
<tr>
<td>B. Freedom from Undesirable Features</td>
<td></td>
</tr>
<tr>
<td>Hazards</td>
<td>+ + + or +</td>
</tr>
<tr>
<td>Need for skill</td>
<td>±&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td>Occurrence of local muscle fatigue at high exercise levels</td>
<td>+</td>
</tr>
<tr>
<td>Need for trained personnel</td>
<td>+ +</td>
</tr>
<tr>
<td>Cost of equipment</td>
<td>+ +&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Ease of maintenance (including need for constant calibration)</td>
<td>+ +</td>
</tr>
<tr>
<td>Freedom from noise</td>
<td>+ +</td>
</tr>
<tr>
<td>Bulk of equipment&lt;sup&gt;h&lt;/sup&gt;</td>
<td>+ +</td>
</tr>
<tr>
<td>Ease of transporting equipment&lt;sup&gt;h&lt;/sup&gt;</td>
<td>+ +</td>
</tr>
<tr>
<td>Need for electricity&lt;sup&gt;h&lt;/sup&gt;</td>
<td>±&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Need for neuromuscular-skeletal coordination</td>
<td>-</td>
</tr>
<tr>
<td>Ease of rate control&lt;sup&gt;h&lt;/sup&gt;</td>
<td>-</td>
</tr>
</tbody>
</table>

* This table is reproduced from the report of a WHO Meeting on Exercise Tests in Relation to Cardiovascular Function (World Health Org. techn. Rep. Ser., 1968, No. 388, p. 11). Each of the four types of test is evaluated according to the criteria listed in the first column. A grading of + + + indicates easiest, greatest freedom from undesirable features, most advantageous, etc.; a grading of - - - indicates most difficult, least freedom from undesirable features, least advantageous, etc. The intermediate point is represented by a grading of ±. Throughout the table, therefore, the greater the number of plus signs (or the fewer the number of minus signs), the fewer the problems presented by the test concerned.

<sup>a</sup> More difficult when the rate and slope are high.
<sup>b</sup> Unnecessary.
<sup>c</sup> Friction type.
<sup>d</sup> Electric type.
<sup>e</sup> Calibration easy for angle, less easy for rate.
<sup>f</sup> Less easy at maximum power.
<sup>g</sup> Can be estimated only.
<sup>h</sup> Less important factor.
<sup>i</sup> Less at low stepping rate, greater at high rate.
TYPES OF ERGOMETER

Bicycle Ergometers

Bicycle ergometers are of two main types, mechanical and electrical, and they may be designed for work in the supine or the upright position, or in both positions. For clinical purposes it is often necessary to carry out exercise tests in the supine position, either because extensive ancillary investigations (such as cardiac catheterization) are being made, or because the condition of the patient precludes exercise in an erect position, or because the objective is to compare circulatory responses to exercise in the two positions.

In the usual mechanical type, a frictional force is developed on or within the bicycle wheel and the work performed is proportional to the product of the applied force and the total number of wheel revolutions. The source of friction is normally a weighted leather belt applied to the outer surface of the driving wheel, but models using weighted brake-shoes have also been devised. In the simplest forms of machine, the frictional force is either calculated from the difference between the applied weights and the reading of a spring balance or is indicated by the position of a calibrated and weighted lever; however, both procedures may lead to systematic error. More sophisticated machines permit the direct application of the desired load. Several problems arise in the use of the simpler machines:

(a) The belt becomes hot, altering the coefficient of friction, and it is not easy to maintain a constant work-load.

(b) The system of belt, weights and levers forms a compound pendulum and the spring balance or load indicator fluctuates wildly during vigorous effort.

(c) Inexperienced subjects find difficulty in maintaining a constant rhythm.

These problems are overcome in the Fleisch ergostat. A servo-mechanism increases the loading automatically as the belt heats and a damping system is provided to minimize oscillations of the belt. The number of pedal revolutions is controlled precisely by a large pointer linked both to the drive of the bicycle and to a synchronous motor through a differential gear. These advantages are offset by a considerable increase in the weight, complexity and price of the apparatus, and the necessity to provide an electricity supply for the synchronous motor.

Electrically braked bicycles provide viscous resistance by moving a conductor through a magnetic or electromagnetic field. In these bicycles the conductor is an iron (or copper) band on the outer part of the wheel; a permanent magnet is moved across the surface of this core as the test progresses, giving a continuous increase of work-load. Other machines transmit the pedal force to a small dynamo. If the field coils of the dynamo are energized from an independent source, it is possible to incorporate a
feed-back mechanism so that the total amount of external work performed is independent of minor variations in pedal speed. The main disadvantages of the electrical machines are the need for an electricity supply and their complexity and cost. Calibration is also much more involved than for the mechanical devices and can only be carried out in specialized biophysical laboratories; unfortunately, the constancy of calibration depends upon the magnetic properties of the core and this is commonly altered during the journey to and from the calibrating laboratory.

The simpler types of bicycle with a mechanical braking system are inexpensive, easy to maintain and can be built in any well-equipped mechanical workshop to meet the specifications of the investigators.

Several types are commercially available. Fig. 12 shows one of the most popular simple designs, that of Von Döbeln (1954). The calibration is arranged so that a scale and pointer (Fig. 13) indicate the approximate work (in kpm) performed by one rotation of the ergometer wheel. Accurate calibration may be done through the application of a standard torque to the pedals. The bicycle is connected to a revolution timer, which records the number of ergometer wheel rotations during the test period, thus permitting estimation of the total work output during the period.
The bicycle should be so constructed as to allow the work rate (work performed per unit of time, expressed in kpm/min or in watts)\(^1\) to be recorded and to permit changes in the work rate while the pedalling rate is kept constant. It should also have a large rate indicator from which the patient can gauge his rate of pedalling, although some adults prefer to keep time with a metronome. The pedal crank length should be 15-20 cm for adults and appropriately less for children. The height of the bicycle seat should be rapidly adjustable. The shape of the seat deserves attention; most people prefer a narrow seat. The mechanically braked bicycle ergometer is portable and in its simpler forms requires no electricity so that it could be used in field studies for testing the maximum aerobic power of primitive populations unfamiliar with this type of muscular activity (Lange Andersen, 1969). If suitable calibration has been carried out, it is also possible to measure accurately the external work performed or the power applied. Another advantage that makes the bicycle, particularly the supine version (see below),

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\(^1\) See page 74 and definitions in Annex 6.
very valuable for clinical use is that the patient's trunk and arms are relatively immobile, thus permitting complicated technical procedures such as catheterization, blood pressure measurements, rebreathing procedures, blood sampling, and the like to be performed. The mechanical efficiency of effort is known rather more precisely than in other types of effort; it varies little over a large range of work intensities and there is only a small variation between individuals. Habituation and learning pose no major problems.

The main drawbacks with bicycle ergometers are related to the occurrence of weakness, fatigue, and pain in the quadriceps muscle and saddle discomfort, which may become intolerable in prolonged exercise, particularly if the patient is untrained in bicycle riding. Strong contraction of the quadriceps during cycling may be sufficient to impair blood flow to that muscle even when exercise is performed at 50-60% of maximum aerobic power. Evidence for this hypothesis is the fact that the blood lactate level is higher during bicycling than during stepping or running (Shephard et al., 1968b).

Difficulties in maintaining the pedal rhythm may also be a problem, particularly in elderly and diseased subjects, and it is not easy for a patient with various leads attached to dismount in an emergency. During vigorous exercise, activity of the pectoral muscles may also impair the quality of the ECG. Calibration should be checked regularly by applying a standard torque. The calibration procedures suggested with commercial versions of the Von Dobeln machine are not very accurate, and for serious scientific study specialized calibration equipment must be borrowed or constructed.

**Bicycling in the supine position**

The initial attempts at bicycling in the supine position may be rather clumsy since this is a totally unfamiliar experience and some practice is usually necessary. It is essential that the subjects be fastened to the supporting bench by appropriate shoulder straps. Furthermore, the feet should be fastened to the pedals in order to prevent slipping during exercise (Fig. 14).

The physiology of exercise in the supine position differs markedly from that in the upright position. The maximum values for oxygen uptake obtained in the supine position are lower than those attained in the upright position. Saltin (1964) found an average of 4.47 litres/min in the upright position, as compared with 3.85 litres/min in the supine position; this difference is surprising in view of the greater stroke volume when supine, but may be due to the fact that only a limited muscle mass can be mobilized in this position.

The haemodynamic responses are also different: there is a substantial initial increase of stroke volume when exercise is performed in the sitting posture, but relatively little change occurs when the subject is lying down.
Different authors have used steps differing greatly in height; single, double, triple, and multiple steps all have their advocates. Sturdy construction is essential and the test is aided by bolting the steps to the floor. A handrail support may be provided for older subjects. The desired height is determined partly by the requirements of rhythm and partly by the requirements of work-load. A rate of less than 60 paces/min is uncomfortably slow, and a rate of more than 180 paces/min leads to tripping. Fortunately the requirements of most exercise tests are satisfied by the range 60-180 paces/min. A total height of 40-50 cm must be climbed during maximum work in fit young subjects. A single step of this height is unfamiliar and is uncomfortable for prolonged use, so for most purposes a double step with each of the two risers 23 cm (9 inches) high is suggested.

Steps should be at least 50 cm (20 inches) wide and 25 cm (or 10 inches) deep. A metronome or a pendulum (a weight attached to a 150-cm length of string may be satisfactory) aids in keeping the rhythm and pace. A convenient staircase for exercise testing is illustrated in Fig. 15. This form was evaluated by an international team of work physiologists in Toronto.
in 1967 (Shephard et al., 1969). The apparatus is cheap and portable, and requires no maintenance, calibration or electricity; in this respect it has many advantages over the bicycle ergometer as a field procedure. Stepping exercise is familiar to almost all people and can be performed easily by subjects of all ages and varying levels of fitness. The intensity of exercise can be readily changed by a simple adjustment of the metronome setting, but some anxiety may arise from tripping at rapid rates.

**FIG. 15**

**SUITABLE STEPS FOR EXERCISE TESTING**

![Step Test Diagram](image)

*From Shephard (1967a).*

The main disadvantage of the step tests is a continuous movement of the arms and head, which creates difficulties when taking physiological measurements. Complicated technical procedures such as cardiac catheterization and cardiac output measurements by rebreathing methods are practically impossible to carry out and even the measurement of blood pressure by the indirect (cuff) method is difficult. However, ECGs of good quality can be obtained during stepping, and oxygen consumption is readily measured.

**Treadmills**

The motor-driven treadmill allows studies of the response of man to walking and running (Fig.16). Treadmills are normally constructed so that both speed and inclination can be varied.
The treadmill "grade" or elevation is defined as the units of elevation per hundred horizontal units; it is expressed as a percentage and is usually set with the aid of a built-in "inclinometer". Speed is conveniently measured in m/s or km/h. The treadmill should be supplied with a speedometer, although for accurate work timing of the belt speed is essential.

Treadmills vary greatly in their size and power, from giant machines able to reach 40 km/h (25 mi/h) to portable devices that may run at speeds of 5-10 km/h (3-6 mi/h). Unless tests are to be performed on champion athletes, a high speed is not essential; few patients can run up an 18% slope at 10 km/h for any length of time, and this intensity of effort can be developed on the simplest form of treadmill. Noise is an important con-
sideration; a poorly constructed or badly maintained treadmill can be an annoyance not only to the investigator but to many of the other occupants of the building.

A safety rail and emergency stop button are also mandatory. The belt should be wide enough to avoid tripping, but not so wide that the patient finds difficulty in grasping the safety rail and stepping to the side platforms when exhausted. A safety mat at the rear of the treadmill is required for maximum effort tests; however, a “safety harness” is probably unnecessary for patients who will exercise at only moderate speeds. Although walking and running are activities familiar to everybody, their performance on a treadmill induces anxiety, since a certain danger of falling off is

FIG. 17
HAND-CRANK ERGOMETER*

*Figure kindly supplied by Richard Lauckner, Berlin.
present. Effects of learning and of habituation, assessed as improvements in work efficiency, are therefore important and play a greater role in treadmill exercise than in bicycling or stepping (Shephard et al., 1968a).

Treadmills have the advantage that the rate of work is constant, is independent of the motivation of the patient, and can be set to any desired level by adjusting the speed and inclination of the belt. They are also more suitable for producing a true maximum oxygen uptake than the other ergometers. However, they are usually bulky, noisy and expensive, may not be easily transported, and require electricity. For these reasons the treadmill is best suited for use in a well-equipped laboratory and is not very practicable for field work.

**Arm Cranks**

Two main types of arm crank can be mentioned: the "double-crank" and the "single-crank" (Fig. 17).

The double-crank ergometer gives substantially lower values for maximum oxygen uptake than bicycle pedalling, but if a large single-crank is used that activates the larger muscle groups of the upper part of the body, then the results with regard to maximum oxygen uptake are comparable with those obtained in other forms of maximum exercise.

German work physiologists have proposed that the length of the single-crank should be one-third of a metre, and that the height of its centre above the floor should be one metre. They also proposed that the cranking rate should be such that:

- 0-100 watts is performed with 25-35 rev/min;
- 100-200 watts is performed with 35-45 rev/min;
- 200-300 watts is performed with 45-55 rev/min.

The arm crank has specific usefulness in the testing of patients with impaired function of the lower limbs, and for this reason it deserves further study. Owing to lack of sufficient information, details on the use of arm cranks will not be given in this manual.
CHAPTER 4

Safety Precautions

No systematic investigation concerning the occurrence of complications in connexion with exercise tests is available. Occasional reports and personal communications disclose, however, that minor complications are not rare and that serious cardiovascular accidents, in a few instances fatal, have been observed. Vasovagal reactions seem to be quite frequent but, if injury is avoided, are usually benign, while cardiac arrhythmias, especially those of ventricular origin, are relatively rare but much feared. Acute cardiac failure is a rare complication observed in severely ill patients with chronic valvular heart disease, and sometimes occurs also in healthy subjects (Bruce et al., 1968). Angina pectoris is usually accepted as a limit to work-load increase and is not regarded as a complication, except in status anginosus; if the ECG is monitored throughout the test, angina occurs rarely.

Careful organization of safety measures is a good assurance against the fatal outcome of the cardiocirculatory accidents that may occur during exercise testing.

Emergency services and safety precautions are mandatory not only when testing cardiac patients but also when testing healthy subjects. Since the occurrence of ventricular tachycardia or ventricular fibrillation is possible in apparently normal people, it is advisable that any team testing normal subjects should be well prepared for emergency situations and that appropriate equipment be available.

Operational Precautions

Requirements concerning personnel

Exercise testing is a highly specialized task and must be performed by well-trained personnel. The measurement of physiological parameters and the conduct of the experiments should be learned in an established laboratory of exercise physiology.

Ideally, the testing team should include four persons: a qualified physician, two technicians, and a nurse. The physician should select the proper
loading pattern, watch the subject for signs and symptoms indicating that exercise should be interrupted, and interpret the ECG and other results, while the technicians and the nurse should take care of the various analytical procedures and calculations, prepare the ECG electrodes, perform the expired gas collection, and take blood pressure, anthropometric, and other miscellaneous measurements. However, if a simple exercise test is used involving stepping or pedalling a bicycle ergometer, with determination only of ECG wave-form, blood pressure and pulse rate, then one experienced person can cope with the whole procedure; but a physician should be at hand if the person in charge of the testing is not medically qualified. With this precautionary measure, accidents due to exhaustion may be prevented and possible emergency situations may be dealt with.

Exercises at low work-loads can in general be conducted by a single individual, but this is not so in the case of the treadmill, which cannot, as a rule, be stopped by the subject himself. Small accidents can have more serious consequences if the patient falls on the treadmill.

The members of the testing team must have a basic understanding of exercise physiology. They must be well acquainted with the testing procedure and the risks involved in different methods of testing. They must be able to recognize signs and symptoms of impending difficulties and be competent to initiate appropriate therapy without delay. Each member should be trained to recognize basic ECG abnormalities.

Safety features of equipment

Treadmills must be equipped with a handrail to prevent falling. Step-tests and bicycle ergometers usually do not require handrail equipment, although elderly subjects may welcome hand support in stepping. The subject must be able to discontinue the test at his will so as to minimize the danger of falls and of exhaustion.

Monitoring equipment

ECG recordings and blood pressure measurements are usually an integral part of the exercise tests. Continuous ECG monitoring on a cathode-ray oscilloscope is not obligatory in all subjects. However, it is recommended particularly when testing cardiovascular patients.

Exertional hypotension has been recognized by many authors as an inadequate and disadvantageous response to exercise; for this reason recording of the systolic blood pressure during exercise is recommended. Details on blood pressure and ECG techniques are given in Chapter 7.
Medical facilities

The room must be equipped with a couch where the patient may lie. A defibrillator is one of the most important pieces of safety equipment. A rubber balloon and face mask of the type used by anaesthiologists and an airway device should also be available to assist respiration if necessary. Emergency medicines must include drugs against arrhythmias (lidocaine or procainamide and quinidine); against severe hypotension or shock (a pressor amine; against angina pectoris (glyceryl trinitrate); against vasovagal reactions (atropine); and against acute cardiac failure (digitalis). Glucose/saline infusion sets should be available.

Clinical Precautions

Medical examination of subjects

Prior to exercise a thorough medical history should be recorded; physical examination should include the cardiorespiratory system with competent evaluation of a multi-lead ECG recording (see Chapter 7 for details).

During the exercise, continuous monitoring of the ECG increases the safety of the test considerably by making it possible to stop it as soon as any significant electrical anomaly appears. It also increases the validity of the test by revealing ECG changes that appear only at the beginning of the test, or disappear rapidly soon after the end of the exercise.

Contraindications for exercise testing

The test cannot be performed routinely if significant locomotor disturbances are present. Impaired neuromuscular function or skeletal abnormality may alter the subject's response to exercise, partly by decreasing his mechanical efficiency (thus vitiating assessments of the cardiorespiratory functions based on work rate) and partly by throwing an excessive strain on specific muscle groups (thus leading to early accumulation of lactate). Anxiety may decisively influence the circulatory response to exercise and may also increase the heart's vulnerability to arrhythmias.

Manifest cardiac failure, symptoms and electrocardiographic signs of impending or acute myocardial infarction and myocarditis, and aortic stenosis are all contraindications for exercise testing. Three months must elapse between an acute episode of myocardial infarction and exercise testing. Acute infectious diseases, unstable metabolic conditions, and the probability of recent pulmonary embolism are also considered as contraindications to exercise testing.

Special precautions must be taken when patients with the following conditions are tested: arterial fibrillation or flutter, high degrees of atrioventri-
cular block, left bundle branch block syndrome, and the Wolff-Parkinson-White syndrome.

Indications for stopping exercise

Discontinuation of the test should be considered as soon as (a) the subject starts complaining of increasing pain in the chest, severe dyspnoea, severe fatigue, faintness and claudication, or (b) the subject shows clinical signs suggestive of an impending emergency situation, including pallor, cold moist skin, cyanosis, staggering, confusion in response to inquiries, the facies of cerebrovascular insufficiency, and head-nodding.

The exact limit of increase of systolic blood pressure as a result of exercise is unknown. An exaggerated increase in relation to age and to clinical condition calls for stopping of the exercise test. Similarly, exertional hypotension or lack of the normal pressure increase during exercise constitutes a contraindication to continued effort.

The ECG should be watched throughout the whole period of the test and if facilities are available an electronic signal average is most helpful. The exercise should preferably be halted if the following ECG changes occur: paroxysmal supraventricular and ventricular arrhythmias, ventricular premature beats appearing before the end of the T-wave, conduction disturbances other than a slight atrioventricular block, and ST depression of horizontal or descending types greater than 0.2 mV. Arrhythmias frequently become more marked immediately after stopping exercise, and if in doubt the investigator should always halt the test.

Some authors maintain that, if no abnormalities occur, the exercise may proceed even up to the attainment of maximum oxygen uptake. Others, who are more conservative, recommend cessation of the exercise when the heart rate reaches the following values:

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Upper limits (beats/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-29</td>
<td>170</td>
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<tr>
<td>30-39</td>
<td>160</td>
</tr>
<tr>
<td>40-49</td>
<td>150</td>
</tr>
<tr>
<td>50-59</td>
<td>140</td>
</tr>
<tr>
<td>60 and over</td>
<td>130</td>
</tr>
</tbody>
</table>

Measurements during recovery period

The frequency of both minor and major complications, including arrhythmias, is probably greater during the recovery period than during the exercise itself. Postural hypotension may develop immediately after exercise, and this can also provoke arrhythmias. Rapid cooling of the body may further
increase the heart's susceptibility to arrhythmias. Unless it is specifically necessary to make recovery observations, the exercise should be gradually tapered off and subjects should be seated in a semi-reclining chair to minimize postural problems. Neither cold nor hot showers should be allowed immediately after the completion of exercise.

A continuation of ECG recording for at least six minutes after exercise is recommended to detect anomalies that may appear only at a late stage or become accentuated during the post-exercise period.
CHAPTER 5

Environmental Specifications and Preparation for Testing

Careful control of environmental conditions and of the state of the subject is essential if the results of exercise tests are to be reproducible and comparable from one laboratory to another. Points to be considered include the following: influence of the time of day; environmental temperature; diet; medication and drugs, including tobacco and alcohol; preliminary rest; anxiety and previous experience of the laboratory; clothing; medical history; and anthropometric measurements.

Time of Day

Many of the functions commonly measured during exercise tests, such as pulse rate and body temperature, show a pronounced circadian rhythm (Mills, 1966). During waking hours a variety of factors also tend to have a harmful effect on human performance. In many populations of the world an increasing dose of tobacco particles and nicotine is taken into the body and leads to bronchospasm, tachycardia, and reduced peripheral blood flow; and in certain occupational groups the tendency to bronchospasm is further enhanced by dusts encountered at work. Again, many subjects spend their working day standing, and this can lead to peripheral pooling of fluid with an increase of extracellular water and a reduction of the central blood volume. For all these reasons the time of day when the measurements are made is of some importance. Unfortunately this factor is often determined by hours of employment and is thus outside the control of the physician. Nevertheless, the time of examination should always be recorded and, whether an individual is being compared with himself or with another, every effort should be made to carry out the test at the same time of day.

Environmental Temperature

A high environmental temperature diverts an increased proportion of the cardiac output to the subcutaneous vessels during rest and submaximum
exercise, so that predictions of maximum oxygen intake based upon the pulse response to a given submaximum load fall into error. Brief exposures to moderate heat have less effect on the maximum oxygen uptake (Saltin, 1964), perhaps because skin blood flow is already maximal. More prolonged exposure to heat leads to reduction of the central blood volume owing to sweating and peripheral pooling of fluid; thus, if the patient is tested at the end of an unduly hot day his maximum oxygen intake may be poor.

The critical range of environmental temperature is from 20°C (68°F) to 30°C (86°F); at 20°C almost all the cutaneous vessels are fully constricted, and at 30°C almost all are fully dilated. The influence of environmental temperature becomes less as the intensity of exercise is increased, since the exercise itself tends to demand full dilatation of the cutaneous vessels. The heat-load imposed by a given air temperature depends also upon the radiant heat, the relative humidity, the air speed, and the nature of the clothing worn during the test. If radiant heating is avoided, the relative humidity is less than 60%, and the air is still, then the laboratory temperature should be kept in the range 18-22°C (64-72°F). The upper limit can be increased by about 2 deg C if the effective temperature is reduced by the use of a large fan.

Exercise tests are not normally conducted in a cold environment, and testing should be discouraged if the room temperature is below 10°C (50°F).

**Dietary Prerequisites**

Both heart rate and ventilation are increased for an hour or more after a heavy meal, and attempts at intensive exercise can lead to vomiting. On the other hand, a complete fast leads to a low blood-sugar level and this also can depress performance. A compromise is thus necessary. On the day before the test the diet is changed as little as possible, while on the test day the subject is permitted a light breakfast (toast or bread, fruit, and a bland drink such as milk or orange juice).

**Drugs**

The patient should not be allowed to take any unusual drugs on the day of testing, and in circumstances where maintenance therapy must be continued (for instance, in a person under digitalis treatment) details of dosage must be specified.

The taking of stimulants—coffee, tea, nicotine and alcohol—is undesirable on the day of investigation, but in the case of out-patient investigations it is difficult to ensure that the patients adhere to the desired regimen. A preliminary one-hour period of observation is thus important not only in permitting the patient to rest, but also in stabilizing the dosage of habitual stimulants.
The importance of adequate preliminary rest is well appreciated by athletes, few of whom would consider volunteering for physiological investigation for several days prior to an important contest. The main adverse effects of previous activity are a peripheral sequestration of fluid leading to a reduction of central blood volume (Lundgren, 1946) and stiffness of the affected muscles. The capacity for prolonged work may also be reduced by exhaustion of muscle glycogen stores.

Ideally the average subject should have a week of rest before the testing, but this is difficult to obtain. However, unusually strenuous exertion and non-essential physical work should be avoided on the day prior to testing. On the day of examination walking and/or driving to the laboratory can be permitted, but no other strenuous activity should be undertaken. The rest period before the test itself should be specified, and should preferably be of at least one hour’s duration.

**Anxiety**

Anxiety on the part of the patient is a greater problem in submaximum than in maximum exercise. The pulse rate and the respiratory quotient at a given submaximum load are both increased by anxiety, and the validity of the usual procedures for interpretation of submaximum test data is compromised. Further, the threshold of various important symptoms, such as angina and dyspnoea, is lowered and depression of the ST segment of the ECG occurs much more readily in an anxious patient than in one who is completely at ease (Dimond, 1961).

Anxiety must thus be kept to a minimum. Where possible, tests should not, for example, be scheduled on the day before a directors’ meeting or ten minutes before the departure of the last bus. The atmosphere of the laboratory and the temperament of the staff should be quiet and reassuring. The number of personnel and the quantity of apparatus in the examination room should be kept to a minimum, and extraneous conversation and street noise should be eliminated as far as possible. Time should be taken to explain the test procedures to the patient and allay any specific fears that he may have. It is sometimes helpful to allow a nervous individual to watch the testing of a previous patient, but this is not advisable if the test involves maximum effort or the taking of blood samples. The effects of anxiety can be overcome quite readily by habituation, i.e., by simple repetition of the entire test procedure at a second visit.

**Clothing**

The deep body temperature can rise as much as 1°C within a few minutes of continuous submaximum exercise. Free loss of heat from the body
is thus important to avoid the occurrence of unduly high pulse rates during the final minutes of exercise. The maximum surface of skin should thus be exposed, light gymnasium shorts being worn where possible.

The subjects should wear their normal shoes, provided these are comfortable and suitable for performing the test. When exercise is performed barefoot or in gym-shoes with low heels and poor ankle support, the chances of a sprained ankle or of an injury to the Achilles tendon are substantially increased.

Medical History

Prior to testing, the medical history of the subject should be recorded with particular regard to the cardiocirculatory and respiratory systems. Such a record would provide: (a) necessary clinical data for proper planning of the test and for evaluation of the results, and (b) indications for safety precautions to be taken (see Chapter 4).

Anthropometric Measurements

The basic measurements recommended prior to exercise testing are the following:

Standing height

This is measured once, to the nearest 0.5 cm. The patient stands without shoes and with his back against the wall-measure; the eyes should be directed straight ahead (the visual axis is horizontal when the top of the external auditory meatus is level with the inferior margin of the orbit), and a set-square should rest on the scalp and against the measure.

Weight

This is measured once, with a lever balance, to the nearest 100 grams; the patient should be clad in light undergarments, without shoes. The weight of the clothing worn by representative individuals is also measured, and the data corrected to a nude weight, except in the case of the step test, where the work calculation must be based on the clothing worn during testing. The balance should be calibrated before and after each study.

Subcutaneous skinfolds

These are measured with calibrated calipers that exert a pressure of 10 g/mm², independent of jaw width. There is a convenient and accurate method for calibrating the jaw pressure at different caliper openings, and evidence exists that a variation in jaw pressure of 1 g/mm² in the average skinfold bite affects the skinfold thickness by no more than 0.2 mm (with a Harpenden caliper). Great care should be taken in locating the skinfold
and in picking it up, since inaccurate procedures may strongly vitiate the measurements.

Firm pressure must be applied with the fingers in lifting the skinfold and supporting it during measurement. A fold comprising skin and subcutaneous tissue should be grasped. If the patient complains of pain, it means that only the dermis is being pinched; a firm grasp of the entire skinfold is usually painless.

The skinfold is grasped about 1 cm above the prescribed site of measurement. The vertical distance from the crest of the fold to the point of measurement should be approximately the same as the thickness of the fold itself. It is desirable to record two measurements and employ their mean for analysis.

Results show considerable observer bias, and it is therefore preferable for one well-trained technician to perform all measurements. If readings are to be interpreted in an absolute sense, the observer should be checked against subjects of known fat thickness. Three skinfolds (triceps, subscapular, and supra-iliac) have been recommended for international standardization.

(a) Triceps skinfold. This is measured on the back of the bare pendant right arm at a level midway between the tip of the acromion and the tip of the olecranon (the mid-point is marked with a skin pencil). The skinfold is lifted parallel to the long axis of the arm, and measurement is made to the nearest 0.5 mm.

(b) Subscapular skinfold. This is measured to the nearest millimetre on the bare chest just below the tip of the right scapula, with the subject standing in a relaxed position.

(c) Supra-iliac skinfold. This is measured to the nearest millimetre just above the right supra-iliac crest in the lateral line.

The values for all three skinfolds should be tabulated individually, though they may be amalgamated later on.

The following additional measurements may be of interest:

Arm circumference

This is measured with a snugly applied tape-measure, in duplicate, to the nearest millimetre, on the bare right arm, relaxed and pendant, midway between the tip of the acromion and the tip of the olecranon.

Sitting height

This is measured once, in the same manner as standing height except that the patient is seated on a stool of standard height.
Shoulder girdle diameter
This is measured in duplicate with obstetric calipers at the level of the acromion processes. The patient stands erect against a wall with the shoulders relaxed. Firm pressure is required to measure the exact dimensions.

Pelvic girdle diameter
This is similarly measured in duplicate; the maximum diameter between the external margins of the iliac crests is recorded.

Bone size
This is measured in duplicate, using obstetric calipers and a steel tape-measure, at the maximum diameters and circumferences of the right humeral and femoral condyles.

Circumference of chest, abdomen, thigh and calf
These measurements are made only in investigations concerned with the detailed distribution of tissue masses, prediction of body-fat content, or changes in body dimensions. A steel tape-measure is used: readings are taken with the patient standing and are recorded to the nearest centimetre.

Standard methods of procedure are as follows:
(a) Chest circumference. This is measured in men on the bare chest at the level of the nipples, at the end of a normal expiration.
(b) Abdomen circumference. This is measured on the bare abdomen at the level of maximum girth.
(c) Thigh circumference. This is measured on the bare right thigh at the level of maximum girth.
(d) Calf circumference. This is measured on the bare right calf at the level of maximum girth.
CHAPTER 6

Proposed Clinical Procedures for Submaximum Exercise Tests

It is widely accepted that the best over-all criterion of cardiorespiratory health is an individual's maximum oxygen uptake, \( \dot{V}_\text{O}_2 \)\text{max}, and it is also held that the maximum oxygen uptake should be measured directly.

The direct measurement of maximum oxygen uptake requires that the subject be exposed to strenuous and exhaustive exercise. This can be done on athletes, but medical, ethical and other reasons make it impossible to carry out such exercise tests on every subject in a population, and it would be most dangerous to expose a sick person or a patient under rehabilitation to such an exhaustive effort. This procedure cannot, therefore, be recommended for routine or for clinical use.

Since this manual is intended as a practical aid in the exercise testing of cardiac patients, children and population groups in general, rather than in testing for sport purposes or for research in exercise physiology, neither maximum exercise tests nor the direct measurement of \( \dot{V}_\text{O}_2 \)\text{max} will be dealt with here.

For clinical purposes a progressive exercise test at increasing submaximum work intensities is safer, easier to perform and yields adequate information. The test should start at a low intensity and the work-load should be increased at regular intervals, usually every four minutes, until a defined limit is reached. It is important that each exercise step should last long enough to establish a steady state with regard to oxygen uptake and usage. If heart rate is monitored continuously it may be used as a guide to determine when the steady state is reached, depending on the age and degree of fitness of the patient. At least four minutes' exercise should be allowed at each load, and physiological measurements should be taken in the last minute of each period.

The ECG should be monitored continuously, e.g., by using an oscilloscope, and it is also helpful to display an averaged ECG signal. The patient should be observed continuously in order to detect signs and symptoms indicating that exercise should be stopped (see Chapter 4).
The maximum oxygen uptake can be directly estimated on the basis of submaximum measurements as described in Chapter 8. Furthermore, the measurements taken during the steady state provide information as to whether the circulatory and respiratory response patterns are "normal" or not. In this way, "abnormal" reactions can be found and related to the level of work at which they occur. ECG abnormalities can be used in the diagnosis and prognosis of ischaemic heart diseases, and the parameters may be used to throw light on the current functional status (see Chapters 9 and 10).

Mode of Performance

Bicycle test

A bicycle ergometer with a mechanical braking system is recommended. Performance should include the following steps:

(a) Safety precautions, preparation of the patient, and adjustment of the environment should be carried out as laid down in Chapters 4 and 5.

(b) The height of the saddle pillar should be adjusted to the size of the patient so that his legs are almost fully extended at the knee-joint when the ball of the foot is applied to the pedals and one pedal is at its lowest position. The patient warms up for four minutes by pedalling at a very low, fixed load (e.g., 10 watts or 60 kpm).

(c) A pedalling rate of 50-60 rev/min\(^1\) should be used in all tests since this is the most comfortable rate for people of average fitness. The pedalling rate should be kept constant with the aid of a tachometer, but a metronome or similar device may be used to help the patient maintain the appropriate rhythm. The patient should always remain seated and not be allowed to lift his body. The exercise proper then begins by setting the workloads at the predetermined values as described below.

(d) The loading for submaximum work depends on the age, fitness, and body weight of the patient. Suggested loads, to be maintained for at least four minutes, are:

- **Children:** Starting at 150 kpm/min, increasing to 300-450-600 kpm/min, etc.
- **Adult males:** Starting at 300 kpm/min, increasing to 600-900, etc. (With athletic subjects the starting load can be 600 or 900 kpm/min.)
- **Adult females:** Starting at 150 kpm/min, increasing to 300-450-600, etc. (With athletic subjects the starting load may be 500 kpm/min.)

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\(^1\) This is also the rate where oxygen uptake is minimal.
In general, it is advisable to be guided by the pulse response to the first load rather than adhere to a rigid schedule. The aim should be to produce four evenly spaced pulse readings over the range 40-80% of aerobic power. The heart rates are recorded at each work-load and will be used for the estimation of maximum oxygen uptake and maximum work output as described in Chapter 8. Alternatively, the graph in Fig. 18 may be used as a guideline to establish the final loading that should be attained as a function of age, sex, and body weight. As an example, a 20- to 29-year-old man weighing 74 kg should be exercised up to 1050 kpm/min, whereas a heavier man (90 kg) in the same age bracket should be exercised up to 1300 kpm/min; in both instances, if the subjects are of average fitness, the heart rate should

*Graph drawn from data in Shephard (1969a). All loads correspond to 75% of maximum aerobic power in a person of average cardiorespiratory fitness. If a subject attains a heart rate 10 beats/min lower than expected, he is of above average fitness; conversely, if his heart rate is 10 beats/min higher than expected, he is unfit. The heart rates corresponding to average fitness in the various age-groups are shown in parentheses (see also Table 6). Cycling was assumed to have a net efficiency of 23%.
attain about 160. A 50- to 59-year-old woman weighing 55 kg should be exercised up to only 420 kpm/min and her heart rate should be 145 (see also data on pulse rates at 75% of maximum aerobic power in Table 6, page 82).

Elderly persons (above 70 years of age) and convalescent subjects should follow the procedure recommended for women. All patients must be individually monitored and those who are more seriously ill must, obviously, be given special, continuous attention.

**Step test**

If the steps illustrated in Fig. 15 are used, the mode of performance of the test is very simple.

**TABLE 4. LOADINGS FOR STEP ERGOMETER IN SUBJECTS OF DIFFERENT AGES AND BODY WEIGHTS**

<table>
<thead>
<tr>
<th>Body weight (kg)</th>
<th>Age-group (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20-29</td>
</tr>
<tr>
<td><strong>Women: Load in ascents/min</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(167)</td>
</tr>
<tr>
<td>36</td>
<td>16</td>
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<tr>
<td>41</td>
<td>17</td>
</tr>
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<td>46</td>
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<td>50</td>
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<td>77</td>
<td>18</td>
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<td>81</td>
<td>18</td>
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<tr>
<td>86</td>
<td>18</td>
</tr>
<tr>
<td>91</td>
<td>18</td>
</tr>
<tr>
<td><strong>Men: Load in ascents/min</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(161)</td>
</tr>
<tr>
<td>50</td>
<td>20</td>
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<td>54</td>
<td>20</td>
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<td>96</td>
<td>21</td>
</tr>
<tr>
<td>100</td>
<td>21</td>
</tr>
</tbody>
</table>

* The loads correspond to 75% of maximum aerobic power in a person of average cardiorespiratory fitness. Stepping was assumed to have a net efficiency of 16%. (Based on data from Shephard, 1969a.)

* The figures in parentheses at the top of each column represent the pulse rates (beats/min) corresponding to average fitness in the age-groups in question. If a person has a pulse rate 10 beats/min lower than expected, he is of above average fitness; conversely, if his pulse rate is 10 beats/min higher than expected he is unfit.
The pattern of ascent and descent is first demonstrated to the patient and the metronome is then set at the desired rate. A suitable starting rhythm for a submaximum test on a young and relatively fit man would be 60 paces (10 ascents) per minute. The patient exercises at this rate for four minutes. He is then asked to increase his speed and the rhythm is increased to 90, 120 and 150 paces/min at 4-min intervals. In a less fit man or a female patient, the starting rhythm is 48 paces/min and the increase may be limited to 72, 96 and 120 paces/min.

The total number of ascents and the actual time should be recorded. In order to calculate the work performed it is necessary to count the total number of ascents and multiply this by the body weight; normally the patient is paced by a metronome. It is vital to ensure that the subject stands erect on the top step after each ascent and places both heels firmly on the ground after each descent. The steps may be bolted to the floor to avoid movement; a padded hand-support is also valuable in giving confidence to older subjects. Table 4 may be used as a guideline for appropriate loading.

**Treadmill test**

Prior to the test the patient stands straddling the belt and grasping the handrails. At a given signal he jumps on to the tread and releases his hand grasp when he is moving confidently. The speed of the treadmill must be checked while the subject is on the belt; if the mill is horizontal the speed may be slowed by the weight of the subject, while if there is a steep incline some acceleration may occur. The choice of speed and slope for a given subject is rather more arbitrary than for step and bicycle ergometer work, but nomograms are now available that permit approximate predictions of the oxygen cost of effort. Suggested loadings are:

(a) Horizontal level, variable speed: starting speed 6 km/h, increasing to 8 km/h, 10 km/h, etc.

(b) Constant speed, increasing inclination:

Walking: speed 6 km/h, slope increasing in steps of 2.5%;
Running: speed 10 km/h, slope increasing in steps of 2.5%.

Lower speeds may be used for subjects with cardiovascular disease.
CHAPTER 7

Techniques for Collection and Evaluation of Cardiovascular and Respiratory Data during Exercise

Cardiovascular Parameters

Analysis of the more fundamental haemodynamic parameters requires measurement of cardiac output, heart rate, pressures in the systemic and pulmonary circulations and electrocardiograms. Some of these measurements can be taken only in specialized hospital laboratories. In particular, the risk involved in heart catheterization should limit such studies to those where the measurements must be taken for medical reasons, or when the investigator himself serves as an experimental subject.

Some circulatory parameters, such as heart rate, brachial artery pressure (by the cuff method) and EEG, are easily obtained. Others, such as cardiac output, may also be performed with bloodless procedures and can thus be conducted in the field laboratory by properly equipped and staffed teams.

Heart rate

The heart rate is easily counted during exercise by palpation of the carotid artery or by auscultation of the heart sounds. The procedure is facilitated by counting the time occupied by 10 heart beats, i.e., by starting a stopwatch at 0 and stopping at 10. Heart rate is then calculated according to the equation:

$$ f_h = \frac{60}{\tau} \times 10 $$

where "f_h" is the heart rate and "\tau" is the duration of 10 beats. Stopwatches are commercially available on which the heart rate may be read directly from the dial.

It is preferable, however, to record the exercise heart rate by means of an electrocardiograph. The ECG makes an important contribution to the safety of a test. It also gives a permanent record and reduces the chances of error. Telemetry systems for ECG transmission could prove very valuable in that they would free the exercising subject from the encumbrance of wires
and cables. There are now several types commercially available. Details on the choice of leads and on ECG recording techniques are given below. The heart rate may be conveniently found by measuring the distance between 7 R-waves (6 intervals) and applying the following formula:

\[ f_h = \frac{b}{a} \times 6 \]

where “a” is the distance between 7 beats and “b” is the distance travelled by the paper in one minute.

The approximate heart rate during exercise may also be monitored by means of cardiotachometers. Several reliable types are commercially available. The use of cardiotachometers is helpful in determining when a relative “steady state” has been reached, and when any determined heart-rate ceiling has been reached in progressive tests.

**Blood pressure**

The pressure in the larger vessels and in the cavities of the heart can be measured by means of catheterization techniques, using either catheter-tip manometers or, less precisely, liquid transmission along the catheter length. However, the use of such techniques is limited to well-equipped and properly staffed hospital laboratories and they should be carried out only when there are medical indications.

Reference is made to a handbook dealing with catheterization techniques and direct blood pressure measurement (Sjöstrand, 1967). Both systolic and diastolic pressures can be measured and the approximate mean pressure is usually indicated by the measuring instrument itself.

The brachial artery pressure may be measured by the conventional cuff method, which, however, has certain disadvantages when used during exercise. Only the systolic blood pressure can be assessed reasonably well during exercise, and readings of 300 mm Hg and more have been recorded without any apparent discomfort or hazard to the patients concerned. Exertional hypotension seems to be recognized by many as an inadequate and disadvantageous response to exercise. For this reason, recording of the systolic blood pressure during exercise is recommended as a safety measure (see Chapter 4). Attempts to measure the diastolic pressure are generally regarded as unsatisfactory. For details on the technique of indirect blood pressure measurement see Rose & Blackburn (1968).

The mean arterial pressure may be calculated from measurements of systolic and diastolic pressure according to the equation:

\[ \text{Mean arterial pressure} = \text{diastolic pressure} + \frac{1}{3} \text{ pulse pressure}. \]

The pulse pressure is the difference between the systolic and the diastolic pressure.
Electrocardiogram

Choice of leads

Before exercise, the classic 12-lead recording is essential as well as the recording from the lead that will be used during the exercise test.

Various methods of recording during exercise have been suggested. Certain bipolar or transthoracic leads increase the QRS amplitude and the ST depression, others seem little sensitive to changes in the electrical position of the heart, while still others are less sensitive to extraneous interference (Blackburn & Katigbak, 1964; Blackburn, 1969).

Various possible ways of recording have been proposed. If four leads can be used, they should be I, II or aVF (aVF electrode and reference electrode placed at the base of the spine, level with the iliac crests), V₂ and V₅; the CH leads (reference electrode placed on the forehead) may also be used. A good solution is a 7-cable lead, with the limb leads placed below each clavicle distally and in the flank above the iliac crest, chest positions being V₄, V₅ and V₆. It is then possible to record I, II, aVF, V₄, V₅ and V₆, which contain all the information available from 12 leads (Blackburn, 1969).

If a bipolar lead system can be used, preference should be given to the lead exploring point V₅; the reference electrode should be placed at the symmetrical point on the right hemithorax (C₅-C₅R) or on the manubrium sterni (CM₅). The neutral electrode may be placed on the back of the neck, the forehead, or the right arm, as convenience dictates.

After exercise, the leads that were used during the test should be supplemented by leads I, II and III, aVL and aVF.

Recording technique

Correct preparation of the skin, which should be reddened by rubbing with ether, and the choice of electrodes are important in order to obtain a readable ECG tracing during the test. Various types of special electrodes have their advocates; as a rule preference should be given to electrodes avoiding direct contact between the skin and the metal by the interposition of a special paste. However, good results can be obtained from standard suction cups if these are carefully applied.

Continuous recording during exercise considerably increases both the safety of the test, by making it possible to stop it as soon as any significant electrical anomaly appears, and its validity, by revealing changes in the ECG that appear only at the commencement of the test or disappear rapidly after the end of exercise (Bellet & Müller, 1965). A continuation of recording for at least six minutes after exercise is desirable, to detect anomalies that may appear only at a late stage or become accentuated during the post-exercise period (Abarquez et al., 1964). A comparison of ECG recordings during bicycle and step tests has been reported by Folli et al. (1965).
Cardiac output

Cardiac output may be measured by either "bloody" or bloodless methods. The "bloody" methods require indwelling catheters in the systemic and pulmonary arteries and should be performed only in well-equipped hospital laboratories and on medical indication. Catheterization techniques should be learned only in specialized laboratories and they will therefore not be dealt with in this manual (for further information, see Sjöstrand, 1967). Both the "bloody" and the bloodless methods of cardiac output determination require highly trained personnel, expensive equipment, and complicated analytical procedures. Only outlines of the techniques will be described here; further details may be found in Degré (1968).

"Bloody" methods

Fick principle. The oxygen content is measured in mixed venous blood (sample taken from pulmonary artery) and in arterial blood, and the arteriovenous oxygen difference is calculated. If the oxygen uptake is measured simultaneously, the cardiac output can be calculated according to the following formula:

\[ \dot{Q} \text{ (ml/min)} = \frac{\dot{V}_{O_2}}{C_{a.o_2} - C_{v.o_2}}. \]

In cases of congenital malformations, with communication between the pulmonary and systemic circulations, blood may be shunted from one circulation to another. This affects the oxygen content of the blood sampled from the different parts of the system and analysis of these differences may permit the diagnosis of such shunts.

Indicator dilution technique. If a known quantity of indicator substance (either a radio-isotope or a dye) is injected into the circulation at one place and samples are then drawn sequentially at another place, the concentration of the indicator at the sampling site will be lower than that at the injection site. A dilution curve can thus be drawn and the blood flow passing the sampling site may be calculated.

According to Degré (1968), if \( \dot{m} \) is the injection rate of the indicator and \( C_t \) is the concentration of indicator at the sampling site at time “t”, then the cardiac output at time “t” is given by the formula:

\[ \dot{Q}_t = \frac{\dot{m}}{C_t}. \]

The time interval between injection and the first appearance of indicator substance at the sampling site is termed the appearance time. The concentration thereafter increases quickly to a maximum, and then decreases in an almost exponential fashion. Before the concentration reaches zero a
new increase occurs as a result of recirculation. Recirculation of the indicator substance makes it impossible to determine the passage time directly. Since disappearance is exponential, the concentration curve may be plotted against time on semilogarithmic paper and the passage time can be found by extrapolation to zero concentration. The mean concentration of indicator substance at the sampling site is determined by dividing the area of the graph (total amount of substance) by the passage time.

**Bloodless methods**

*Inhalation of a foreign gas.* A foreign gas (e.g., acetylene) with a known blood solubility coefficient is inhaled from an air or oxygen mixture. The uptake of the foreign gas is measured over unit time and from this figure and the solubility of the foreign gas in the blood, the cardiac output can be calculated.

The method was introduced by Grollman (1929) and further worked out by Christensen (1931).

The acetylene method has been considerably refined in recent years by shortening the rebreathing period to a maximum of 7 seconds (thus avoiding significant recirculation); by using lower concentrations of acetylene (maximum 1%), which are subjectively more acceptable and avoid danger of explosion; by more accurate determinations of the solubility of acetylene; and by the development of modern techniques of acetylene analysis (gas chromatography, infra-red analysis, mass spectrography). The main disadvantages of the method are the need for regular and deep breathing (60 breaths per minute, which is unnatural except during heavy exercise) and the assumption that gas mixing in the lungs is adequate. As with most other techniques for the measurement of cardiac output, trained personnel are needed to take carefully timed gas samples, and the necessary analytical equipment is quite expensive.

*CO₂-rebreathing procedure.* The arteriovenous CO₂ difference and the CO₂ output are measured, and the cardiac output is calculated according to Fick's principle:

\[
\dot{Q} = \frac{V_{CO₂}}{C_{a,CO₂} - C_{v,CO₂}}.
\]

The content of CO₂ in mixed venous blood is measured by one of two possible rebreathing procedures (Campbell & Howell, 1960; Defares, 1958). The content of CO₂ in arterial blood can be derived in various ways (see Klausen, 1965; Lambertsen & Benjamin, 1959; Magel & Lange Andersen, 1968; Bar-Or et al., 1969).

Reference must be made to a standard CO₂ dissociation curve, and this creates problems in many clinical disorders. As with the acetylene method, regular and deep breathing is required together with adequate gas mixing; the equipment is also expensive and the arteriovenous CO₂ difference
is too small to permit accurate measurements at rest. None of the bloodless procedures has yet reached the point where it can confidently be recommended for general use. However, in view of the many disadvantages of catheterization, including time, cost, disturbance of the patient's basal metabolic state, prescription of sedative medication, and inherent risks, the use of bloodless rather than "bloody" techniques for the estimation of cardiac output is preferable.

Other cardiovascular parameters

Oxygen pulse

The oxygen pulse is defined as the oxygen uptake divided by the heart rate, and is calculated accordingly:

\[ \text{Oxygen pulse (ml/beat)} = \frac{V_{O_2}}{f_h}. \]

The oxygen pulse is a function of the stroke volume and of the arteriovenous oxygen difference.

Stroke volume

When cardiac output and heart rate are measured, the stroke volume can be calculated:

\[ Q_s (ml) = \frac{\dot{Q}}{f_h}. \]

Arteriovenous oxygen difference

When oxygen uptake and cardiac output are measured, the arteriovenous oxygen difference can be calculated:

\[ C_{a, o_2} - C_{v, o_2} (ml/litre) = \frac{V_{O_2}}{\dot{Q}}. \]

Left ventricular work

When cardiac output and mean blood pressure in the aorta are measured, the work rate of the left ventricle (\(\dot{W}_l\)) can be calculated:

\[ \dot{W}_l (kpm/min) = \dot{Q} \times \text{BP}_{\text{mean}}. \]

Several authors calculate an indirect index of left ventricular work from measurements of arterial blood pressure (by an indirect method) and heart rate.

Ritmeester & Boutkan (unpublished report, 1956) propose the following equation:

\[ \dot{W}_h = f_h \times (P_{S, a} - P_{D, a} + 100) \times (P_{S, a} + P_{D, a})/2 \times 10^6, \]
where \( \dot{W}_h \) is the work of the heart, \( f_h \) is the heart rate, \( P_{S,a} \) is the systolic pressure, and \( P_{D,a} \) is the diastolic pressure. Hellerstein et al. (1967) recommend the use of the following index:

\[
\dot{W}_h = P_{S,a} \times f_h .
\]

**Resistance and conductance**

A pressure gradient between two areas in a vessel causes blood to flow from the high pressure area towards the low pressure area, while resistance impedes the flow. This can be expressed mathematically as follows:

\[
Q = \frac{\Delta P}{R} \quad \text{or} \quad R = \frac{\Delta P}{Q},
\]

where \( Q \) is the blood flow (litres/min), \( \Delta P \) is the pressure gradient (mm Hg), and \( R \) is the resistance.\(^1\)

Resistance cannot be measured directly; it can only be calculated from the above formula. \( R \) is expressed in arbitrary units or in dynes sec/cm\(^5\) (see also Table 1).

Since the pressure in the right atrium is close to zero, the total resistance in the systemic circulation is:

\[
R_{\text{total}} \text{ (in arbitrary units)} = \frac{BP_{\text{mean}}}{Q}
\]

or

\[
R_{\text{total}} \text{ (dynes sec/cm}^5\text{)} = \frac{BP_{\text{mean}}}{Q} \times 1.333 \times 60.
\]

Conductance is the reciprocal of resistance: \( C = \frac{1}{R} \).

**Heart size**

Heart volume is measured by standard X-ray techniques, using frontal and lateral films. A focus to film distance of 2 m and an object to film distance of 10 cm for the sagittal film and of 20 cm for the transverse film are recommended. The films are taken at the end of an ordinary inspiration and no synchronization between exposure and phase of the heart cycle is necessary.

Details of the technique are given in several publications to which the reader is referred (Jonsel, 1939; Ammundsen, 1959; Reindell et al., 1967).

\( ^1 \) In arbitrary units.
**Total haemoglobin and blood volume**

The total blood volume (TBV) is defined as the sum of the cells and plasma within the vascular system. The methods available for measuring TBV are based on dilution procedures. A known amount of an indicator substance (a radioisotope or a dye) is injected into the blood; after a given time, blood is withdrawn and the final concentration of indicator is determined and used to calculate the red cell volume (RCV) and/or the plasma volume (PV). Sjöstrand (1948) has worked out a method for determining total haemoglobin, and hence TBV, by introducing a known quantity of carbon monoxide into the blood through inhalation and subsequently measuring the concentration of carboxyhaemoglobin in the peripheral blood. Reference is made to this paper for details.

**Blood lactate**

Capillary blood sampled from the finger-tip (or ear-lobe) after warming of the hand by immersion in water at 45°C may be used for the determination of blood lactate.

Either the photometric method, originally described by Barker & Summerson (1941) and later modified by Strøm (1949), or the micro-method described by Scholander & Bradstreet (1962) may be used. Enzyme methods have also been described (for references see Shephard et al., 1968a).

**Respiratory Parameters**

It is desirable that at least the following respiratory measurements be taken:

1. Respiratory minute volume (gas volume expired per unit time);
2. Respiratory frequency (with subsequent calculation of tidal volume);
3. Respiratory gas exchange, including oxygen uptake, carbon dioxide output, and respiratory gas exchange ratio.

The use of an open-circuit system is recommended for taking these measurements. Closed-circuit systems suffer from several important defects, namely:

1. Erroneous results can arise from displacement of the end-tidal position or alterations of thoracic blood volume.
2. Volume errors can arise from temperature changes, particularly at high metabolic loads.
3. The performance of the available apparatus is inadequate in terms of resistance and inertia at high metabolic loads.
(4) Leakage, for which both systems should be checked before use, has a much greater effect on the results in a closed than in an open system.

All determinations of respiratory gas exchange require careful analytical work. Techniques of measurement should preferably be learned in a reference laboratory to avoid systematic errors.

Collection of expired gas

Expired gas may be collected in bags (Douglas bags) or spirometer tanks. Several types of Douglas bags made of vinyl plastic or heavy-duty polyethylene are commercially available in various sizes (100-250 litres). It is important to select a broad-necked design. A flexible side-arm tube for direct sampling of gas is sometimes provided, but it is preferable to collect from the tube leading to the spirometer after the bag has been partially emptied. When using Douglas bags in the collection of expired air, leakage of CO₂ due to diffusion is unavoidable; however, the effects of such diffusion may be minimized if the bags are filled almost to the limit of their capacity, and if they are sampled and emptied through a gas-meter as quickly as possible after collection.

If a conventional bell spirometer is used instead, problems may arise from filling resistance, inertial overshoot, and changes in expired gas temperature. The first two problems may be largely overcome by using a lightweight bell or dry plastic spirometer of sufficient size (bell capacity of at least 100-150 litres). The use of a bell spirometer has the advantage that the respiratory movements can be recorded by means of a conventional recording drum. Several dry gas-meters (respirometers) are available that meter the expired gas volume immediately and allow aliquot air samples to be drawn for further analysis. However, in general, they have too high a resistance and too low an accuracy for on-line use. The portable Max-Planck respirometer is designed for field use and for measurements of light effort; it will not accommodate the gas volumes encountered in heavy exercise testing.

Face masks are difficult to use in exercise tests owing to problems of dead space and leakage. A conventional nose-clip and a broad-flanged mouthpiece fitted to a low-resistance (less than 5 cm H₂O pressure at a flow of 300 litres/min), low-dead-space (preferably below 50 ml) respiratory valve is recommended. The opening pressure of the wet valve should not exceed 2.5 cm H₂O pressure.

Connecting tubes and stopcocks should have a smooth internal bore, with a diameter of at least 30 mm, and sudden angulation of the air-stream should be avoided. Non-corrugated flexible hose should be used with as short a length as possible (about 1 m). The total expiratory gas line should be free to move in two directions, perpendicular to one another.
system should have a resistance to air flow not exceeding 1.5 cm H₂O at a flow rate of 200 litres/min.

The three-way stopcock connecting the patient to the Douglas bag or spirometer should be opened at the end of an expiration when exercise starts and closed, also at the end of an expiration, when exercise stops. The time during which the collection is made must be noted accurately and is used in the calculation of the results.

Mouthpieces should be washed with soap and water and, if they will withstand boiling, it is recommended that they be sterilized in boiling water for 3-5 min. When boiling is impossible, the use of a standard bactericide at the recommended dosage is advised. Nose-clips need not be sterilized except after they have been used on a subject with nasal secretions or a superficial skin infection. Valves and connexions should be washed with soap and water after use. Even when using the open system, washing of the tubing past the expiratory valves is desirable as bacteriological studies have shown that micro-organisms can regurgitate past one-way valves.

**Recording of breathing frequency**

The breathing rate (breaths per minute) can be counted simply by observing the patient; if a spirometer is used the respiratory movements are recorded by the writing device and recording drum. Several other more complicated systems have been designed to indicate breathing frequency.

The tidal volume \(V_T\), in ml, is calculated from the measurement of respiratory minute volume \((\dot{V}_E)\) and breathing frequency \(f_R\) according to the following formula:

\[
V_T = \frac{\dot{V}_E}{f_R}.
\]

**Gas metering**

Either large bell spirometers or some type of gas-meter, either wet or dry, can be used to measure gas volumes. Dry gas-meters are handy instruments in field studies but they require frequent calibration. When dry or wet gas-meters are used it is important not to exceed the specified rate of operation in order to secure accurate measurements. Various flow-meters are also available. These may be used in metering gas volume, but in general they are more expensive and offer little advantage.

After the expired air has been collected in bags it is metered by passing it either into a bell spirometer or through a gas meter. Various arrangements, such as air pumps and other control devices, may be employed to secure standard operation and to facilitate the procedure.

The temperature of the collected gas must be recorded with an accuracy of 0.2 deg C. This can be done by inserting a thermometer in the exit part
of the gas-meter or at the top of the spirometer bell. It is important to allow time for equilibration of temperature between the thermometer, air and water, and this is one rather serious drawback to on-line measurements of gas volume.

The barometric air pressure must be recorded to the nearest mm Hg, using an accurate barometer (preferably a mercury barometer).

The expired gas volume should be expressed under STPD (standard temperature and pressure, dry gas) conditions, using the appropriate factors. Alternatively, a small desk-top computer may be programmed to carry out the necessary calculations.

**Gas sampling**

Aliquot gas samples may be collected in glass syringes (50 ml or larger), in small bags within an air-tight metal or glass container, or in traditional mercury sampling tubes. The gas samples should preferably be analysed as quickly as possible, although their composition remains unchanged for at least six hours in well-greased syringes or mercury sampling tubes.

If glass syringes are used they should be initially dried and cleaned, and then lubricated carefully with a compound that does not absorb CO$_2$; ethylene glycol is recommended.

**Gas analysis**

Either chemical or physical methods may be employed, and an accuracy within ±0.05% should be obtained. Chemical methods require less expensive apparatus and have slightly greater precision if employed by well-trained personnel; however, they are more time-consuming than the physical methods and periodic checks of technique should be made against known gas mixtures if serious errors are to be avoided.

**Chemical methods**

*Haldane gas analyser* (Haldane & Priestley, 1935). Carbon dioxide is absorbed in potassium hydroxide solution, and oxygen is subsequently absorbed in a solution of either pyrogallic acid or of anthraquinone (which gives a faster reaction). The remaining gases in the sample are normally inert, nitrogen making up the major portion. This method being a volumetric one, the initial sample volume must be recorded and the percentage of carbon dioxide and oxygen in the dry mixture calculated from respective decrements of gas volume in the two absorption chambers.

An accuracy of ±0.02% is claimed. The analysis takes from five to ten minutes to perform, depending on the design (original Haldane or Lloyd modification) and the rate of the oxygen-absorbing reaction.
Scholander 0.5-ml gas analyser (Scholander, 1947). This method is also volumetric. It uses a 10% solution of potassium hydroxide as CO₂ absorber and a solution of sodium anthraquinone-β-sulfonate as oxygen absorber. It has the same accuracy as the Haldane method but is rather more liable to systematic error. It requires a smaller air sample (0.5 ml is sufficient) and an experienced analyst can perform a single analysis in 6-8 minutes.

Physical methods

There are several physical methods of carrying out gas analysis. The apparatus required involves a substantial capital outlay, but in a busy laboratory may ultimately prove cheaper than a team of well-trained Haldane analysts. In order to operate the physical analysers with sufficient precision, careful and frequent calibration is necessary; a supply of gas cylinders of known composition is thus required. Details of the various techniques have been described by White (1958), but an outline of the methods more frequently used is given below.

**Thermal conductivity method.** This method is based on the principle that when the resistance wire is heated in the path of a gas stream, the heat generated by the wire is conducted away at a rate proportional to the thermal conductivity of the particular gas. A hot filament, when heated by a constant power input, has a well-defined resistance to electrical current at any given temperature. As heat is conducted away differentially from the hot filament by different gases the temperature of the filament changes; this causes a change in its electrical resistance that can be converted electronically into a current signal.

Thermal conductivity methods provide a reliable, although rather slow, means of analysing the CO₂ content of respiratory gas. They have occasionally been used for the measurement of oxygen concentrations, but this is not to be recommended since the effect of varying O₂ concentrations on thermal conductivity is slight.

**Paramagnetic oxygen analysis.** The partial pressure of oxygen influences the forces developed in a magnetic field, and this principle is utilized in the construction of paramagnetic oxygen analysers. These instruments give reliable measurements of oxygen tension, which can be converted to concentration (%v/v of dry gas). The instruments can be calibrated manometrically and are well suited to respiratory gas analysis in the laboratory.

**Infra-red carbon dioxide gas analysers.** Carbon dioxide and many other hetero-atomic gases absorb light strongly in the infra-red region of the spectrum; this principle is utilized in the infra-red CO₂ gas analysers. Several instruments suitable for respiratory gas analysis are commercially available.
Calculations: Oxygen uptake and respiratory gas exchange ratio

Since all gas volumes must be corrected to STPD it is essential that gas temperature and barometric pressure be recorded. One convenient way of converting gas volumes that are collected and metered at ATPS (ambient...

FIG. 19
NOMOGRAM FOR DETERMINING STPD FACTORS FOR REDUCTION OF SATURATED GAS VOLUMES TO DRY VOLUMES AT 0°C AND 760 mm Hg*

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* From Consolazio et al. (1963).
FIG. 20
NOMOGRAM FOR CALCULATING RESPIRATORY QUOTIENT (GAS EXCHANGE RATIO) AND TRUE OXYGEN FROM ANALYSES OF EXPIRED AIR

*From Consolazio et al. (1963).
temperature and pressure, saturated with vapour) to STPD volumes is to multiply the ATPS volume by the STPD factor shown in Fig. 19 (Consolazio et al., 1963). The observed gas temperature is plotted on scale A or B, and the ambient barometric pressure on scale C. A line is drawn between the two points, and the STPD factor is read off scale D or E respectively. An alternative and even simpler procedure is to programme a small desk-top computer to convert ATPS to STPD values.

In order to calculate oxygen uptake ($V_{O_2}$) from measurements of expired air volume (at STPD), Consolazio et al. (1963) introduced the term "true oxygen". True oxygen is defined as the factor by which the expired air volume (at STPD) should be multiplied in order to calculate the oxygen uptake.

The true-oxygen factor is calculated according to the formula:

$$\text{True oxygen} = \% N_2 \text{ in expired air} \times 0.265 - \% O_2 \text{ in expired air}.$$  

The respiratory gas exchange ratio (R) is calculated according to the following formula:

$$R = \frac{\% CO_2 \text{ in expired air} - 0.03}{\text{True oxygen}}.$$  

True oxygen and R may be read off a nomogram, such as that shown in Fig. 20. In this nomogram, the observed values (in % dry air) for the CO$_2$ and O$_2$ concentrations in the expired air are plotted on scales A and B respectively. A line is drawn between the two points, and the "true oxygen factor" and the respiratory gas exchange ratio (R) are read off scales D and C respectively. Alternatively, these values may be calculated on small desk-top computers, thus eliminating observer errors in the reading of charts.

Examples of protocols for the tabulation of data where the results are calculated without the aid of a computer (A) and with a desk-top computer (B) are given opposite.

The machine prints out:

- ($V_E$)$_{BTPS}$ (litres/min)
- ($V_E$)$_{STPD}$ (litres/min)
- ($V_{O_2}$)$_{STPD}$ (litres/min)
- R
### A. WITHOUT COMPUTER

<table>
<thead>
<tr>
<th>Sampling time</th>
<th>Gas temp. (°C)</th>
<th>STPD factor</th>
<th>BTPS factor</th>
<th>Ventilation</th>
<th>Expired air</th>
<th>Oxygen uptake (litres/min)</th>
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<td>litres ATPS</td>
<td>litres/min STPD</td>
<td>litres/min BTPS</td>
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</table>

* Body temperature and pressure, saturated with vapour.

### B. WITH DESK-TOP COMPUTER

<table>
<thead>
<tr>
<th>Spirometer reading</th>
<th>Gas temp. (°C)</th>
<th>Water vapour (mm Hg)</th>
<th>Barometric pressure (mm Hg)</th>
<th>O₂ (%)</th>
<th>CO₂ (%)</th>
</tr>
</thead>
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CHAPTER 8

Expression of Results: Maximum Work Output and Maximum Oxygen Uptake

The physiological data obtained during submaximum work may be expressed in the following ways:

(1) in relation to work rate, e.g., at 300-450-600 kpm/min, etc.;

(2) in relation to metabolic load, e.g., at 1.0-1.5-2.0 litres/min oxygen uptake, etc.; and

(3) in relation to a percentage of the maximum oxygen uptake, e.g., at 25%-50%-75%.

Maximum work output ($W_{\text{max}}$) and maximum oxygen uptake ($\dot{V}_{O_2}_{\text{max}}$)—i.e., the amount of work performed and oxygen consumed at maximal heart rate—are the most important criteria for assessing physical fitness in general and cardiorespiratory function in particular (see Fig. 22).

Work Output

In bicycling and in stepping, the work output is usually expressed in kilopond-metres (kpm) or kilogram-metres (kgm), which are equivalent in unit gravitational field, whereas work rate is expressed in kpm/min, kgm/min, or watts.

The conversion of kpm/min into watts, or vice versa, can be made according to the equation: 1 watt \(\approx\) 6 kpm/min, or 1 kpm/min \(\approx\) 0.167 watt. The ordinate axis of the graph in Fig. 18 may be used as a nomogram for the interconversion of watts and kpm/min.

Bicycle test

The net mechanical efficiency of bicycle riding has been assessed in many laboratories and averages about 22% \(\pm\) 4%.
The total work output ($W_t$) during the whole testing period "t" can be calculated as follows:

$$W_t = w \times a,$$

where "w" is the work (indicated in kpm on the machine scale) performed during one rotation of the ergometer wheel, and "a" is the number of rotations of the wheel in time "t", which is indicated by the revolution counter.

The work rate $\dot{W}$ in kpm/min would therefore be: $W_t / t$.

An example of a protocol for calculating the work rate on a mechanical bicycle ergometer is given below.

<table>
<thead>
<tr>
<th>Exercise periods</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration (t) of each exercise period, in minutes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loads (w) on ergometer wheel in kpm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number (a) of wheel rotations in time t</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Work output in time t ($W_t = w \times a$) in kpm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Work rate ($\dot{W} = W_t / t$) in kpm/min</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Step test**

The mechanical efficiency of effort in stepping is lower and a little more variable than that on the bicycle ergometer (16%, as compared with 22%). However, it is still quite practical to equate work performed and oxygen consumed, if facilities are not available for oxygen analysis. A load of 700 kpm/min on the step test is approximately equivalent to a load of 1000 kpm/min on the bicycle ergometer.

If care is taken to ensure complete ascent and descent, the work performed in time "t" ($W_t$) can be estimated with reasonable accuracy from the step height, body weight and number of ascents according to the formula:

$$W_t (\text{kpm}) = \text{body weight (kg)} \times \text{height of steps (m)} \times \text{number of ascents in time "t"}.$$
Treadmill test

The work output cannot be directly calculated in activities such as walking and running. All measurements, and in particular oxygen uptake (see below), must therefore be related to inclination and speed.

Maximum Oxygen Uptake

The oxygen uptake and the net mechanical efficiency of submaximum "steady state" exercises should be calculated and expressed in relation to work output. Maximum oxygen uptake can be determined in various ways:

Direct methods

These involve performing muscular exercise at increasing intensities and establishing the level of work rate above which a further increase in work output does not bring about any increase in oxygen uptake. This "plateauing" of oxygen uptake is the best single criterion that the maximum value has been reached (Fig. 21). Subsidiary criteria are a blood lactate level of over 100 mg/100 ml (Fig. 21), a gas exchange ratio higher than 1.15, and a pulse rate in excess of the predicted maximum.

FIG. 21
DIRECT DETERMINATION OF MAXIMUM OXYGEN UPTAKE:
OXYGEN UPTAKE IN RELATION TO WORK OUTPUT ON BICYCLE ERGOMETER AND BLOOD LACTATE LEVEL 4-6 MINUTES AFTER CESSION OF EXERCISE

[Diagram showing oxygen uptake and blood lactate level in relation to work performed]

*Submaximum exercise for 6 min; maximum exercise for 3 min. The maximum oxygen uptake corresponds to the level of work where a further increase in work output does not result in any higher oxygen uptake. (Figure kindly supplied by Professor K. Lange Andersen.)
Indirect methods

**Fitting of a linear regression line**

This method is based on the establishment of the linear relation (see Fig. 2) that exists between heart rate and oxygen uptake measured when the metabolic rate, circulation, and respiration have reached a "steady state" response to submaximum work, and subsequent extrapolation to "maximum" heart rate (Fig. 22).

![Image of Fig. 22: Indirect estimation of maximum work and of maximum oxygen uptake.](image)

The procedure involves making the subject exercise at several workloads (see Chapter 6) and measuring oxygen uptake and heart rate when a steady state response is reached at each load. The heart rates are plotted against the corresponding values of oxygen consumption and a straight line is fitted, either by eye or by the method of least squares. This line is extrapolated to the predicted maximum heart rate; the corresponding oxygen consumption, \( (V_{O_2})_{\text{max}} \), can then be read off. Since the maximum heart rate is age-dependent (see Fig. 1), the value needed for the extrapolation should be previously obtained from the graph in Fig. 23. It is advisable that a graph of this type be constructed relative to the population group to which the subjects under study belong. Some authors avoid this complication by extrapolating to heart rate 170 instead of the maximum and using, therefore, \( (V_{O_2})_{170} \) instead of \( (V_{O_2})_{\text{max}} \).
FIG. 23
RELATION BETWEEN MAXIMUM RATE AND AGE*

*Figure kindly supplied by Professor K. Lange Andersen.

FIG. 24
RELATION BETWEEN WORK RATE AND OXYGEN UPTAKE IN BICYCLE TESTING*

*Figure kindly supplied by Professor K. Lange Andersen.

This indirect method may be simplified by establishing the linear relationship between heart rate and work performed (instead of oxygen uptake), with subsequent extrapolation to maximum (or 170, if so preferred) heart rate. In this way, the maximum work rate ($W_{\text{max}}$)—or, alternatively, $W_{170}$—
can be evaluated (see Fig. 22). Maximum oxygen uptake can then be more accurately estimated by using the relationship between work rate and oxygen uptake shown in Fig. 24. Table 5 exemplifies mean values of $\dot{V}_{O_2}\text{max}$.

### TABLE 5. TYPICAL MEAN VALUES OF MAXIMUM OXYGEN UPTAKE (ml/min/kg body-wt, STPD)*

<table>
<thead>
<tr>
<th>Age-group (years)</th>
<th>Men</th>
<th>Women</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-29</td>
<td>44</td>
<td>36</td>
</tr>
<tr>
<td>30-39</td>
<td>42</td>
<td>34</td>
</tr>
<tr>
<td>40-49</td>
<td>39</td>
<td>33</td>
</tr>
<tr>
<td>50-59</td>
<td>36</td>
<td>29</td>
</tr>
<tr>
<td>60-69</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>70-79</td>
<td>27</td>
<td></td>
</tr>
</tbody>
</table>

* Norwegian population sample (unpublished data supplied by Professor K. Lange Andersen).

The fitting of the line requires at least three, and preferably four, points ranging from a heart rate of 110-120 to one of about 150-180, depending upon the age of the subject. The main disadvantage of this approach is that the fitting of the linear regression line gives an excessive weight to the lowest points on the line and these points are rather readily distorted by anxiety and an increase in environmental temperature. Empirically established age-dependent mean maximum values of oxygen uptake for a given population are often used as an approximation for the maximum heart rate of an individual.

### Use of a nomogram

Åstrand & Ryhming (1954) have proposed nomograms for the evaluation of oxygen uptake during stepping or cycling submaximum exercises. Pulse rate is measured at one or more submaximum loads, together with the corresponding oxygen consumption or work rate. The maximum oxygen uptake is then estimated directly from the nomograms.

In using either of these nomograms corrections should be made for variations in maximum heart rate with age. Fig. 25 shows the Åstrand-Ryhming nomogram.

With the aid of this nomogram it is possible to compute the maximum oxygen uptake from the heart rate measured after a 6-minute step test at the rate of 22 steps per minute. The step height is different for males and females. This nomogram can also be used with a bicycle ergometer. Maximum oxygen uptake can be extrapolated as follows: (1) draw a horizontal line through the body-weight scale "b", in the case of a step test, or the work-level scale "a", in the case of a bicycle test, and read the corresponding oxygen consumption on scale 1. (2) Draw a line through this
last value and the exercise heart rate value on scale 2 and read \((\dot{V}_o)_\text{max}\) on scale 3. The nomogram was constructed on the basis of measurements taken on young adults. For persons of 25 years and over, the estimated value for \((\dot{V}_o)_\text{max}\) must be multiplied by the appropriate correction factor, as shown in the following table (Astrand, 1960).

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Correction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>1.00</td>
</tr>
<tr>
<td>35</td>
<td>0.87</td>
</tr>
<tr>
<td>45</td>
<td>0.78</td>
</tr>
<tr>
<td>55</td>
<td>0.71</td>
</tr>
<tr>
<td>65</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Another nomogram for evaluating \((\dot{V}_o)_\text{max}\) from step tests was published by Margaria et al. (1965).
In activities such as walking and running on a treadmill, the work output cannot be directly calculated. The oxygen uptake must therefore be related to slope and speed. In the case of walking the relation is not linear, the rate of oxygen requirement increasing markedly at higher speeds. The oxygen cost of running bears a more nearly linear relationship to speeds, so that it is most efficient to walk at slow speeds and run at faster speeds.

*Redrawn from Shephard (1969b).*
Shephard (1969b) has constructed a nomogram that gives the energy requirements of running at various speeds and slopes (Fig. 26). Data on the energy requirements of treadmill exercise have also been published by Bobbert (1960).

Use of an arbitrary formula

Von Döbeln et al. (1967) have recently devised a formula relating maximum oxygen uptake to age and heart rate during submaximum exercise on the bicycle ergometer. Their equation is:

$$ (\dot{V}_\text{O}_2)_{\text{max}} = 1.29 \sqrt{\frac{L}{f_h - 60}} e^{-0.00884T} $$

where “L” is the bicycle ergometer load in kpm/min, “f_h” is the heart rate after six minutes’ exercise at this load, and “T” is the subject’s age in years. This new formula is claimed by the authors to give a more accurate estimation than the Astrand-Ryhming nomogram; the method of calculation implies an increase of efficiency with an increase of maximum oxygen uptake, since $$(\dot{V}_\text{O}_2)_{\text{max}}$$ varies as the square root of L.

Accuracy of methods

The accuracy of the various methods for estimating the maximum oxygen uptake is not greater than ±10% (Lange Andersen & Smith Sivertsen, 1966; Shephard et al., 1968a). Hence, the optimum approach for future standardization might well be to report all data—oxygen consumption, work-load and ECG findings—at pulse rates corresponding to a fixed fraction of aerobic power; 75% seems a convenient arbitrary level, since it is below the threshold for substantial anaerobic work. A suitable table of pulse rates for this purpose is presented in Table 6.

**TABLE 6. APPROXIMATE PULSE RATES (BEATS/MIN) AT SELECTED PERCENTAGES OF MAXIMUM AEROBIC POWER**

<table>
<thead>
<tr>
<th>Percentage of aerobic power</th>
<th>Age (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20-29</td>
</tr>
<tr>
<td></td>
<td>Men</td>
</tr>
<tr>
<td>40</td>
<td>115</td>
</tr>
<tr>
<td>60</td>
<td>141</td>
</tr>
<tr>
<td>76</td>
<td>161</td>
</tr>
<tr>
<td>100</td>
<td>195</td>
</tr>
</tbody>
</table>

* Data from Shephard (1969a).
CHAPTER 9

Evaluation of Results:
Diagnostic and Prognostic Value of Exercise Tests

Physical training brings about local changes in the muscles, improved
neuromuscular co-ordination of activities, and a series of more general
cardiorespiratory changes, as follows:

(1) an increase of maximum respiratory minute volume in exercise;
(2) possibly a slight increase in oxygen diffusing capacity;
(3) 10-30% increase of maximum oxygen intake (depending on initial
fitness);
(4) an increase in stroke volume and maximum cardiac output;
(5) an increase in volume of the heart shadow;
(6) an increase in total haemoglobin and blood volume.

While all the above values are higher in physically fit subjects, the
following are lower:

(1) heart rate at rest and at a given effort;
(2) systolic pressure at a given effort;
(3) lactic acid level in blood at a given effort.

The following parameters usually remain unchanged, regardless of the
degree of physical fitness:

(1) total lung volume (although the vital capacity may be increased by
exercises strengthening the thoracic musculature);
(2) the oxygen consumed by the left ventricle (more work is performed
for a given myocardial oxygen consumption; this reflects the fact that
external work is only a small component of total myocardial work).

All the variables may undergo very rapid changes with alterations of
activity pattern, and this is one reason why the so-called “normal” values
found in the literature are often discordant. It is also why it is advisable
that each investigator elaborate his own set of standard values relative to
the type of patients or to the population group he is studying. A few
weeks of total inactivity are enough to decrease the fitness of a subject,
with deterioration of many physiological functions; on the other hand, physical training can quickly improve the work capacity of a sedentary individual. This is true not only of healthy subjects but also of sick people.

If the end-points of exercise testing are $W_{\text{max}}$ and $(V_{O_2})_{\text{max}}$ (see Chapter 8), the cardiorespiratory fitness of an individual can be assessed according to Fig. 27, which is self-explanatory. As an example: if $W_{\text{max}}$ and $(V_{O_2})_{\text{max}}$ are higher (or lower) than the mean for the population group to which the subject belongs, then the subject’s fitness is above (or below) average; or, in the case of a patient (coronary or otherwise) who has undergone a certain treatment or a rehabilitation programme, the improvement of his health and, consequently, of his physical fitness can be assessed by comparing the post-treatment $W_{\text{max}}$ and $(V_{O_2})_{\text{max}}$ values with the pre-treatment ones: if the former are higher, it means that cardiorespiratory fitness has improved.

*Redrawn from Lange Andersen (1968), copyright Academic Press.

Alternatively, if the method illustrated in Fig. 18 is used, and the end-point is therefore heart rate, physical fitness can be assessed by comparing the subject’s heart rate at the work-load corresponding to his age, sex, and body weight with the average heart rate of the population group to which he belongs (values in parentheses in the figure; see also Table 6); if his exercise
heart rate is 10 beats/min higher than expected, he is unfit; if it is less than expected, he is of above average fitness.

Exercise tests are of special value in the diagnosis of coronary diseases for they enable the clinician to detect coronary insufficiency in a patient whose resting ECG is normal, to assess the coronary vascular status of a subject whose resting ECG is already abnormal, and to help interpret a pathological resting tracing in a patient in whom coronary disease is doubtful because of age, case-history or clinical data.

In labile arterial hypertension and in neurocirculatory asthenia, the exercise test may also be of diagnostic interest. In other cardiovascular or pulmonary diseases the exercise test has no value from the strictly diagnostic viewpoint, but many be of considerable aid in defining the functional status of the patient with a view to determining his work capacity, establishing a rehabilitation programme or deciding whether an operation is indicated.

Types and Intensity of Exercise in the Diagnosis of Cardiovascular Diseases

The bicycle ergometer advocated for a long time by Scandinavian authors may have some advantages in coronary cases, mainly because (a) the same position can be maintained afterwards, which is highly desirable for correct interpretation of the ECG record, and (b) if a supine version is used, safety is also increased owing to the position of the subject (it is difficult for a patient fitted with various leads to dismount from an upright bicycle ergometer in an emergency).

The relative value of the different exercise tests remains debatable; although Master's step test (or one of its variants) has the advantage of simplicity, the bicycle ergometer test in the upright position makes it possible to attain high heart rates gradually and under conditions that may offer more comfort and safety to a patient who is unwell. Changes in the ECG tracing may also be followed with the patient in the same position during exercise and recovery periods if the bicycle is used.

The Master test has been much utilized in the diagnosis of coronary insufficiency (Master & Rosenfeld, 1967). Usually the technique advocated by Master and the tables drawn up by him are applied; however, some authors consider that Master's tables, which take weight into account, add a personal factor to the test instead of eliminating it. In any case, the Master test calls for some criticism: recording of the ECGs during exercise is easy enough, but the tracing recorded during the test has to be compared with tracings recorded in the supine position before and after exercise; the heart rate reached during the test is not usually very high and does not represent a sufficiently large fraction of the theoretical maximum rate according to the age of the subject (it is estimated that the rate reached during
exercise should, apart from contraindications, attain about 75% of the maximal theoretical rate based on the age of the patient); and the test causes considerable variations in heart rates between individuals.

Variants of the Master test have been suggested to overcome the above drawbacks: gradual increase in the number of "ascents"; a single step of variable height; carriage of a load by the patient; etc.

The increasing-load treadmill has also been suggested, i.e., a treadmill test with a gradual increase in speed and slope; this exercise makes it possible to increase the heart rate up to its maximum limit, if no other factor arises to interfere with the test. However, the inherent logistic and operational difficulties limit the use of a treadmill to a well-equipped laboratory.

As to the intensity of the tests, it is desirable that the effort be of gradually increasing intensity so as to raise the heart rate as much as possible. In this way the diagnostic validity of the test is increased, since the percentage of negative tests in confirmed coronary cases decreases without an undue increase of false positive tests. The occurrence of negative tests in confirmed coronary cases drops from 80% in the single Master test to 45% in the more strenuous double Master test, to 10% if the test is continued until the symptom of angina develops, and to almost zero if the test is prolonged up to the maximum heart rate (Bellet & Müller, 1965; McAlpin & Kattus, 1966). Similarly, the percentage of ischaemic ST segments reported in a population clinically free from cardiovascular complaints increased from zero in the single Master test, to 3% in the double Master test, to more than 7% if the test was continued until heart rate reached 150 beats/min, and to more than 10% for exhaustive exercise (Abarquez et al., 1964). The diagnostic limitations of the Master two-step test have been described by Master & Rosenfeld (1967).

Coronary Complaints

ECG criteria of coronary insufficiency during exercise

Depression of the ST segment

A change in the ST segment is the essential element in the exercise ECG of coronary cases. Study of this criterion calls for the accurate measurement of an ST depression equal to about 0.01 or 0.02 mV, and therefore it requires the definition of a stable reference line based on cardiac cycles rigorously situated on the same horizontal level. This reference line can be constructed by using a small transparent plastic rule to join either several PR segments or several points of junction located between the PR segment and the QRS complex or the PQ junction (Q-Q base-line). Alternatively, a series of 16-32 cycles may be averaged by electronic devices; such procedures are essential if significance is to be attached to measurements of 0.01 mV.
In any case, care must be taken to avoid error due to the interference of a negative T-wave of auricular repolarization (T_a-wave) with the commencement of the ST segment, particularly if the PR space is short and the T_a-wave is long, as is the case in tachycardia. The following cases must be taken into consideration:

(a) Depression of the ST segment of ischaemic type. To be indicative of ischaemia, the ST segment must be either a horizontal straight line (Fig. 28, A) or a straight, or slightly convex, line sloping downwards and bending upwards in the form of a sickle (Fig. 28, B). At present the ischaemic ST is regarded by many authors as the essential criterion and by some even as the only valid diagnostic criterion of myocardial ischaemia (Sheffield & Reeves, 1965).

(b) Depression of the ischaemic ST segment at its origin. Before it can be regarded as significant, the ST depression, according to some authors, should exceed 0.05 mV or even 0.1 mV, especially in the presence of tachy-
cardia. Although some writers do not assign diagnostic value to the extent of ST depression, all nevertheless stress its prognostic importance (Robb & Marks, 1967). The displacement can, if necessary, be divided into three categories of depression: 0.01-0.09 mV; 0.1-0.19 mV; 0.2 mV and above.

(c) JST depression. Depression of the J point with a rapid and almost vertical climb towards the isoelectric level generally has little significance, especially in the presence of tachycardia. Its appearance may be due to (a) interference from the T-wave or a normal type of electric repolarization connected with the increase in effort and in heart rate, (b) to the intervention of the autonomous nervous system, or (c) to hyperventilation and an associated respiratory alkalosis. Deep inhalation and the administration of parasympatholytic or adrenolytic drugs, as well as decubitus, may restore a more "normal" appearance to this complex. However, certain authors feel that a considerable JST displacement during exercise (exceeding 0.2 mV) or a gradual climb towards the base-line may have a certain ischaemic significance (Fig. 29).

FIG. 29
DEPRESSION OF "JST" TYPE WITH LOWERING OF POINT J AND RAPID RETURN OF THE ST SLOPE TO THE BASE LINE (POINT X)*

* Figure kindly supplied by Professor H. Denolin.

(d) Duration of the ST depression. This should be greater than 0.08 sec. This criterion makes it easier to separate ischaemic ST depression from the JST aspect.

(e) QX/QT ratio. If the duration of QX (interval between the commencement of QRS and the point where the depressed segment returns to the base-line (see Fig. 28, B) exceeds half the QT duration (i.e., if the QX/QT ratio is more than 50), there may be ischaemia, even if the ST slope towards the base-line is reminiscent of the JST aspect and the drop beneath the line is less than 0.2 mV. This criterion, however, is strongly debated.
(f) *Rise in the ST segment.* When occurring alone, a rise in the ST segment may be found in normal subjects as well as in ischaemic cases; under resting conditions it may appear saddle-shaped, with the concavity directed upwards and sometimes exceeding 0.2 mV in the left precordial leads, and it may disappear momentarily during exercise. However, a rise in the ST segment accompanied by a depression in the opposite leads always indicates serious ischaemia, with a risk of acute complications in the corresponding sector of the myocardium.

**Changes in the T-wave**

An isolated T-wave change during exercise is, in general, hardly specific. Continuous 24-hour ECG recordings have shown that in 30% of "normal" subjects (i.e., those with no cardiac complaints) transitory changes in the T-wave may occur, an increase in amplitude being twice as frequent as a decrease. These T-wave variations are brought about by tachycardia, nervous excitation, effort, mental activity, change of position, eating a meal, coffee, tobacco, etc.

However, the appearance of a pointed and elevated T-wave in V4 with three times the amplitude (or more than 0.5 mV) always indicates serious myocardial ischaemia. It may be accompanied by a decrease in the amplitude of the R-wave or a rise in the ST segment. Some authors believe that a 25% decrease in the T-wave during or after exercise, as compared with the resting value, is suspect and that a 50% decrease probably signifies coronary insufficiency. Moreover, a flattening of the T-wave after exercise is seen more often among sedentary subjects in their forties than among heavy manual workers. The value of these various changes has not yet been defined precisely (Puddu et al., 1965).

The significance of the return to positive value in exercise of a T-wave inverted as a result of an old myocardial lesion is also debated. Such a return of negative T-waves to positive voltages has been observed in healthy subjects (Master & Rosenfeld, 1967).

As to frank but isolated inversion of the T-wave, whether constant or only post-extrasystolic, this is sometimes regarded as pathological or at least suspect if it exceeds 0.2 mV and shows a lengthened QT in the presence of a normal electrolyte balance. Certain authors, however, feel that it is only in association with an ischaemic ST that the T-wave inversion becomes of pathological significance and represents a factor aggravating the prognosis (Mattingly, 1962; Blackburn & Katigbak, 1964).

**Changes in the TU segment and the U-wave**

A TU displacement is always pathological, both during rest and during exercise, whether or not associated with an ischaemic ST. A negative U-wave is generally regarded as pathological in the resting subject, except in aVR and in III, if T is negative. During exercise an increase or decrease in
the amplitude of the U-wave, dependent in particular on the heart rate, may be normal. On the other hand, inversion of this wave is always pathological (Bruce et al., 1956).

Other changes

The amplitude of the P-wave may triple during exercise; this is not pathological. The PR space may shorten during exercise both in the normal subject and in coronary cases; it is said to shorten always in chronic pulmonary patients with marked dyspnoea.

A large change of amplitude, i.e., a reduction of R to at least 60% of its resting value as well as a variation in the QRS axis during exercise exceeding +30° or −20°, or a variation in the T axis, can be regarded as pathological.

Transitory disturbances of conduction, possibly proceeding as far as a block of the left or right branch, may also reveal coronary ischaemia (perhaps localized to the septal tissues), but it may also be merely the result of an increase in heart rate beyond a critical threshold value. Lengthening of the duration of intraventricular conduction has not yet any well-defined meaning.

Ventricular or auricular extrasystoles should be regarded as possibly pathological only if they are numerous and multifocal. As to attacks of arrhythmia during or after exercise (auricular fibrillation, ventricular or supraventricular tachycardia), their significance is a matter of controversy. At present it is impossible to come to any definite decision as regards the ischaemic specificity of these attacks which, according to prolonged and continuous dynamic checks, may occur from time to time in normal subjects. The possibility of such accidents, however, calls for the continuous monitoring of exercise tests, and also the immediate availability of means for rapid defibrillation.

Exercise tests in the determination of coronary capacity

By measuring the heart rate at the end of exercise and comparing it with the theoretical maximum heart rate for the age of the subject, the rate of reduction of coronary capacity in the subject under test can be evaluated (Sheffield & Reeves, 1965).

For the functional assessment of a patient with a confirmed but stabilized coronary condition—to determine his physical fitness, for example—the ECG should be monitored continuously at gradually increasing levels of exercise. The presence of alterations in the resting ECG does not constitute a contraindication to the test since the aim is evaluation and not diagnosis. Exercise capacity is defined as the metabolic level just below that where well-marked ischaemic changes develop, such as increasing pain without change in the ECG, supraventricular or paroxysmal ventricular arrhythmia or ventricular extrasystoles occurring before the end of the T-wave, disturbance of conduction, or depression of the ST segment of ischaemic type
It should be noted that the ingestion of drugs may influence the changes in the ST segment, so that the test should be repeated not less than two or three weeks after such medication has ceased.

**Exercise tests in the diagnosis of non-specific repolarization anomalies**

It is becoming increasingly evident that healthy subjects may present "non-specific" changes in the ST segment and the T-wave that cannot be explained by a heart condition or any apparent medicinal, metabolic or electrolytic cause. These anomalies are not exceptional (1-5% of cases according to some authors) and are sometimes difficult to diagnose. Various tests have been proposed to reveal the non-coronary origin of such anomalies: the recording of the ECG in decubitus and while standing; hyperventilation test; recording on an empty stomach and after a meal; potassium test. However, the exercise test is of particular value in that it can cause resting-state ECG anomalies to regress or disappear.

**Validity of exercise tests**

It should be remembered that "false negative" cases exist—i.e., subjects with a heart condition in whom exertional anginal pain develops without any specific change occurring in the ECG; there are also coronary patients whose resting ECG is highly abnormal but who do not present any additional changes during exercise, or even during an attack of angina. Furthermore, it should be mentioned that there are also a number of "false positive" cases, i.e., clinical conditions that in the absence of any organic pathological coronary changes may bring about or accentuate ECG changes during exercise. The following may be mentioned in particular:

1. relative or functional insufficiency of coronary output (e.g., left ventricular hypertrophy, mitral stenosis);
2. electrolyte imbalance (e.g., diuretics);
3. hormone imbalance (e.g., adrenal hyperfunction);
4. haemoglobin deficit or blocking (e.g., severe anaemia, increased level of carboxyhaemoglobin);
5. impairment of oxygen transport (e.g., hypoxia);
6. various drugs (e.g., epinephrine, digitalis, quinine, nicotine);
7. meals (post-prandial hypokalaemia, probably caused by insulin action);
8. hyperventilation (changes of intracellular potassium concentration as a result of respiratory alkalosis): on the other hand, this may sometimes prevent or improve ST changes due to neurocirculatory asthenia, left ventricular hypertrophy, pericarditis or saturation with digitalis;
Many of these conditions, probably as a result of the hypokalaemia that they bring about (Kwoczynsky et al., 1961), may accentuate ECG anomalies accompanying mild exercise even in the absence of coronary insufficiency. This applies in particular to digitalis which, because of its influence on the transmembrane ionic transport or on the permeability of the cell membrane, renders the interpretation of ECG anomalies during exercise subject to considerable difficulty.

Other measurements taken during exercise

Changes in the ECG during exercise not only make it possible to reach an accurate diagnosis in coronary heart patients when the resting ECG is normal, but also permit assessment of the coronary capacity in a patient whose coronary insufficiency is already apparent while resting, or in a patient recovering from myocardial infarction. However, there are non-coronary causes for apparently ischaemic ECG changes. Thus, where there is lack of agreement between the ECG findings and the clinical data, a thorough analysis of the context must be made, with a search for possible alternative causes of the ECG changes and perhaps recourse to other tests.

It is probable that these alternative causes depend on the same cellular mechanism as hypoxia itself, and that the presence of an ischaemic ST appearance gives no absolute diagnostic certainty of the ischaemic nature of the anomaly or of the nature of the causal heart condition.

Additional haemodynamic measurements may contribute useful information, for although the change in the contour of the ECG is of considerable value from the diagnostic and prognostic viewpoint, it does not by itself enable the work capacity of a patient to be determined precisely; the lack of relationship between the resting ECG and functional capacity should be remembered here. Haemodynamic tests carried out on coronary heart cases may possibly reveal a hypokinetic state, with a reduction of cardiac output and of stroke volume at a given work-load. The oxygen consumption and change of heart rate, in addition to the changes in the shape of the ECG tracing, are important factors in defining the clinical condition of the patient at a given work-load.

Study of the relationship between haemodynamic or metabolic behaviour and certain morphological data may also reveal pathological changes in functional status and the degree of cardiac compensation (for example, relationship between the maximum oxygen pulse and the volume of the cardiac shadow).

For additional information on ECG in exercise testing, see: Sandberg (1961); Folli et al. (1965); Blomqvist (1965); Riva et al. (1967); Berkson et al. (1966); Bruce et al. (1966); Areskog et al. (1937); Blackburn (1969).
Arterial Hypertension

As was mentioned in Chapter 1, normal subjects always show elevation of the mean peripheral arterial pressure at the beginning of effort. There is an almost linear relationship between loading and increase in mean peripheral blood pressure; if the effort is prolonged, the arterial pressure may show a slight decrease in comparison with the initial exercise value. Age has a marked influence, the systolic pressure increasing much more markedly in older people.

Information regarding changes in central (aortic) blood pressure during exercise is still scanty and controversial. In a hypertensive subject at rest, cardiac output is usually normal while peripheral vascular resistance is increased; however, in young hypertensive subjects cardiac output may sometimes be increased while vascular resistance remains normal, and in older hypertensive subjects the cardiac output may decrease. In some instances the initial phase of hypertensive disease is represented by a state of hyperkinesis and normal resistance that progressively evolves towards a state of hypokinesis with higher resistance.

During exercise, cardiac output may be lower in hypertensive than in normal patients and the arteriovenous difference may be greater, even at low work-loads. The systemic arterial pressure is always higher in the hypertensive than in the normotensive subject during exercise, but the difference is particularly marked in older patients. However, the exercise-induced increase of arterial pressure is proportionally the same in hypertensive and normotensive patients. Vascular resistance is usually higher even in the young hypertensive, but the reasons for this are not yet clearly defined.

Diagnostic interpretation of arterial pressure changes

Diagnosis of hypertension

The elevation of blood pressure that is observed during effort in known hypertensive subjects does not yield any significant diagnostic information. In cases of labile hypertension, i.e., when the resting blood pressure reverts to normal after a few days of rest, the response to effort is similar to that observed in permanent hypertension, the vascular resistance becoming abnormally high. Since exercise provokes hypertension, it may be useful in disclosing labile hypertension and in indicating the need for hypotensive treatment. In other conditions (such as mitral stenosis and aortic stenosis) arterial pressure falls during exercise; this indicates a low myocardial reserve and is a sign of severe disease.

Some works worthy of study in connexion with blood pressure changes in exercise are those by Logan & Bruce (1958), Bruce et al. (1959), Carlsten
& Grimby (1966), Sannerstedt (1966), Eich et al. (1966), Amery et al. (1967), Bellet & Roman (1967), and Hamer (1968).

**Diagnosis of myocardial status in hypertension**

Detection of latent coronary insufficiency in hypertensive subjects is particularly important. The prevalence of ECG abnormalities under effort is much higher in hypertensive subjects, and is more marked as the arterial pressure increases. This is probably related both to the increased work of the left ventricle and to the presence of a coronary disease, and it has important diagnostic and prognostic significance.

**Work of the left ventricle**

Analysis of this parameter, and, consequently, of certain symptoms (e.g., crises of angina) or of the effect of certain drugs, requires a knowledge of the relationship between arterial pressure, cardiac frequency, and other parameters. Measurements of blood pressure are therefore indispensable not only in assessing the performance of effort tests but also in evaluating the status of the myocardium.

**Valvular and Congenital Diseases**

Exercise tests have little diagnostic value in valvular disorders and congenital malformations. Nevertheless, they aid in the assessment of effort tolerance better than the anamnesis or the clinical examination can do and, therefore, they may yield useful information regarding fitness for work or the advisability of surgical treatment.

In such cases less weight is given to changes in the ECG and the arterial pressure, and more emphasis is placed on the assessment of myocardial adaptation and of valvular obstacles either at the pulmonary level (pulmonary hypertension, dyspnoea, changes in respiratory function) or at the peripheral level (metabolic derangements secondary to a poor adaption of cardiac output or augmentation of arterial desaturation).

**Mitral stenosis**

Of the various valvular ailments, mitral stenosis has been studied the most extensively. The following parameters are commonly considered:

(a) **Oxygen consumption.** The "on-transient" (adaptation phase) is protracted, and although steady state values are usually normal during submaximum efforts, \( (\dot{V}_O_2)_{\text{max}} \) may be markedly reduced (Denolin et al., 1953; Blackmon et al., 1967).

(b) **Ventilation in relation to oxygen consumption.** Hyperventilation often occurs in mitral stenosis as a consequence of insufficient cardiac output
or of changes in pulmonary function and brings about an abnormal elevation of the ventilatory equivalent for oxygen. Hyperventilation is often accompanied by a fall in the arterial CO₂ tension.

(c) Heart rate. This increases excessively in relation to effort, particularly in severe cases. The maximum oxygen pulse is markedly reduced (Frick, 1968).

(d) Cardiac output. In spite of marked tachycardia, cardiac output increases only slightly owing to the lack of increases in stroke volume.

(e) Lactic acid. The blood lactate level during and immediately after exercise increases disproportionately as a consequence of inadequate peripheral blood flow.

(f) Pulmonary arterial pressure. This increases disproportionately with progression of the disease. In the early stages, it increases moderately under effort, and this increase parallels that seen in the left ventricle and the pulmonary capillaries. As the disease progresses, however, the pulmonary arterial pressure increases disproportionately relative both to left ventricular and capillary pressures and to the increase in cardiac output. At this stage there are thus secondary alterations in the pulmonary arterial system that lead to an increase of resistance. Such changes indicate also that the disease is progressing. More elaborate indices of the performance have been proposed, such as the fitness index of Bruce et al. (1956); however, these methods of expressing data do not appear to offer any diagnostic advantage.

The simplest and most sensitive tools for assessing the severity of mitral stenosis during effort are the determination of ventilatory equivalent for oxygen and heart rate at specified fractions of aerobic power. The measurement of pulmonary arterial pressure during effort in either the sitting or the supine position contributes to assessment of the degree of stenosis and may be indispensable in surgical diagnosis. Tests based on the determination of heart rate are still applicable in the presence of auricular fibrillation.

The responses discussed above are not specific to mitral lesions. They simply indicate impaired function of the left ventricle. All other diseases that reduce left ventricular output during exercise may give rise to the same cardiorespiratory effects.

Mitral insufficiency, aortic stenosis and aortic insufficiency

These and other more complex valvular lesions have not been studied so extensively. In general, the haemodynamic and respiratory effect of valvular lesions is the failure of the left ventricular output to increase during effort.
**Congenital malformations**

Maladaptation to effort will manifest itself as an inability of the heart to supply enough oxygen to the peripheral tissues, mainly because the resistance of the pulmonary vasculature is increased, thus preventing an adequate increase in cardiac output. Other reasons may be the appearance or the enhancement of a right to left shunt accompanied by desaturation of the arterial blood and, more rarely, insufficient adaptation of the left ventricle.

The effort tests for congenital malformations are the same as those used for the general assessment of work capacity. In children who are old enough to ride a bicycle, the simple measurement of the heart rate during progressive effort is perfectly practicable. The simple cardiorespiratory tests may be supplemented by measurements of arterial oxygen saturation. A decrease in oxygen saturation during effort may mean either development of a shunt or reversal of an intra- or extra-cardiac shunt. The changes in right ventricular and pulmonary arterial pressure and in the vascular resistance of the lungs indicate the degree of maladaptation to effort, and may help in medical and surgical diagnosis.

In patients with congenital malformations, as in those with acquired valvular disease, aptitude for effort does not correspond closely to the haemodynamic changes; physical capacity is also influenced by body weight, age, and degree of physical training. Better assessments of the severity of the disease can sometimes be achieved by comparing the results of the exercise tests with the cardiac volume or with the total haemoglobin. If, for instance, the working capacity is poor in relation to heart volume, this may imply substantial right ventricular hypertrophy due to pulmonary stenosis or pulmonary hypertension; if, on the other hand, the physical working capacity is poor but the ratio of working capacity to heart volume is normal, the patient merely lacks training. For more information on exercise testing in congenital heart diseases, see Jonsson et al. (1957) and Frick et al. (1966).

**Neurocirculatory Asthenia**

This ailment is characterized by poor vasomotor regulation and by a lower degree of contraction of the resistance vessels. Venous tone is reduced, and an abnormal proportion of blood is peripherally distributed. The resting cardiac output may also be increased, usually with an increased heart rate rather than an increased stroke volume.

Exercise tests are often useful in the diagnosis of neurocirculatory asthenia. They may reveal an abnormally high heart rate and cardiac output in moderate work, with deficient circulation to the peripheral muscles, a high lactic acid level in the blood, and a lower work capacity. ECG abnormalities may also appear both during and after exercise.
Changes in work performance are particularly apparent when cardiac volume and total haemoglobin level are related to the PWC\textsubscript{170}. However, if the test is carried through to maximum effort, it is found that the ratio of work performed to heart volume is essentially normal, although the aerobic power is poor. In contrast, patients with myocardial disease have a decreased ratio of work performed to heart volume in heavy and maximum effort (Holmgren, 1967).

**Chronic Pulmonary Diseases**

It would be impossible to review here all the alterations of respiratory physiopathology that may occur in different pulmonary diseases. The mechanisms involved are so complex and the tests proposed for the assessment of pulmonary function are so varied that we shall deal only with some parameters that permit (a) assessment of ventilatory function under effort, and (b) detection of possible respiratory insufficiency. Suggested references are: Denolin et al., 1964, 1966; Sadoul et al., 1966; Armstrong et al., 1966; McIlroy, 1968; Anderson & Shephard, 1968.

**Ventilation**

If the respiratory frequency becomes too high, it suggests that respiratory function is abnormal. This is particularly true if the heart rate remains within the limits anticipated for a given work-load. However, several chronic pneumopathies (particularly those of obstructive type) do not give rise to an excessive respiratory frequency, while certain cardiac ailments may give rise to a disproportionately high respiratory frequency and to poor physical capacity as a consequence of secondary pulmonary insufficiency. An abnormally high minute ventilation may also occur in some pulmonary diseases, more commonly in restrictive than in obstructive ailments. This is demonstrated by calculation of the respiratory equivalent for oxygen: $\text{REO}_2 = (\dot{V}_O_2)_{STPD}/V_{BTPS}$.

The respiratory equivalent does not normally exceed 30, even during relatively strenuous effort.

As with respiratory frequency, the increase in ventilation volume is not specific to pulmonary ailments but is observed also in hyperthyroidism, anxiety, heart disease, etc.

The *dyspnoea index* has been proposed by some authors as a more sensitive tool in diagnosis. It is defined as $100 \times \dot{V}_E/MVV_{100}$ (%), where $\dot{V}_E$ is the expiratory minute volume and “MVV\textsubscript{100}” is the maximum voluntary ventilation at 100 breaths/min. In a normal subject under heavy effort the value of this index is less than 50%, but in chronic pneumopathies, and particularly in obstructive ailments without hyperventilation, it increases markedly since the MVV\textsubscript{100} is small. The MVV is normally measured.
at rest, although recent work shows it to be increased somewhat by exhaust­
ing exercise.

A progressive increase of ventilation during moderate effort may also
indicate some pulmonary abnormality. In this respect, the study of the
expiratory minute volume ($V_E$) would be useful. Bonjer (1968a) introduced
the concept of a ventilation performance index, which is similar to the
Leistungspulsindex (oxygen pulse) but indicates how much $V_E$ increases at
each load increment, and compares actually measured data with normal
values for subjects of the same sex and body build.

The French school has developed the criterion of maximum tolerated
power (puissance maximale supportée), which corresponds to the most
intense “steady state” effort that can be sustained for 20 minutes (i.e.,
when ventilation between the 10th and the 20th minute of effort remains
constant to within 5%, with a ventilatory equivalent of less that 30 and a
respiratory gas exchange ratio of less than 1). This test is of particular
interest for the assessment of chronic pneumopathies of occupational
origin. A steady state work-load of 720 kpm (120 watts) should be sus­
tained by a healthy adult male. Unfortunately, as in other tests, a poor
performance is not specific to pulmonary syndromes but may occur also as
a consequence of heart disease.

**Blood gases**

The following values may be considered as normal:

<table>
<thead>
<tr>
<th></th>
<th>At rest</th>
<th>At 75% of maximum effort</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_a,O_2$ (%)</td>
<td>93-98</td>
<td>Same</td>
</tr>
<tr>
<td>$P_a,O_2$ (mm Hg)</td>
<td>83-100</td>
<td>Same</td>
</tr>
<tr>
<td>$P_a,CO_2$ (mm Hg)</td>
<td>36-47</td>
<td>Slightly less</td>
</tr>
</tbody>
</table>
| Arterial pH       | 7.35-7.45         | Lower ($-0.03$ at bicycle
|                   |                   | ergometer load of 720
|                   |                   | kpm or 120 watts)       |

If the resting values are normal and the effort values are abnormal
(e.g., lower $S_a,O_2$ or $P_a,O_2$, markedly lower pH, marked increase or decrease
in $P_a,CO_2$), it suggests that pulmonary function is impaired. However,
alteration of the blood gas values is not specific to pulmonary diseases.
For instance, a fall in $P_a,CO_2$ is simply a consequence of alveolar hyper­
ventilation, regardless of cause. Similarly, $P_a,O_2$ and $S_a,O_2$ may decrease
markedly in congenital malformations with a right-left shunt. Metabolic
acidosis is observed in all cases of peripheral circulatory maladaptation,
whether due to insufficient cardiac output or to insufficient distribution
of output to the active muscles, as in neurocirculatory asthenia and patients
with poor physical fitness.

Excessive CO$_2$ retention is probably the most specific sign of insufficient
alveolar ventilation; when it is accompanied by oxygen desaturation of the
arterial blood it indicates a combination of ventilatory insufficiency and pulmonary disorder or congenital heart disease.

Assuming that there is no cardiac malformation, then an increase of $P_{a,CO_2}$ in association with a decrease of $S_{a,\text{O}_2}$ suggests a disorder of obstructive type, such as bronchitis or emphysema; if marked hyperventilation is associated with a fall in $P_{a,\text{O}_2}$ while the $P_{a,\text{CO}_2}$ remains normal, this suggests pulmonary fibrosis.

**Diffusing capacity or transfer factor**

It is generally admitted that measurement of the diffusing capacity is useful in the assessment of pulmonary function. It is also generally admitted that diffusing capacity increases during effort, but there are many differences in the techniques used and in the way of expressing results, so that a standard, practical application of this parameter cannot be envisaged yet.

**Haemodynamic parameters**

It is commonly held that determinations of exercise heart rate are of no interest in the diagnosis of a chronic pulmonary ailment or in the assessment of physical fitness in a patient suffering from respiratory insufficiency. As noted earlier, oxygen uptake depends more on cardiac output than on alveolar ventilation, and the heart rate during effort may follow a normal pattern even in serious pneumopathies. It seems that there is no relation between changes in heart rate and changes in pulmonary arterial pressure.

The effort ECG may be useful in the detection of a myocardial or coronary ailment, but for the diagnosis of chronic cor pulmonale it is of little value.

Another important parameter to be taken into consideration is the pulmonary arterial pressure during effort. If this increases during effort while the capillary (wedge) pressure remains the same, it implies that pathological lesions are present in the arterial and arteriolar system. The appearance of pulmonary hypertension disproportionate to the imposed work-load (i.e., a mean pressure higher than 25 mm in young subjects undergoing efforts of moderate intensity, or higher than 35 mm Hg in subjects over 50 years old and in young subjects undergoing an exhaustive effort) is of particular interest (a) in the diagnosis of vascular complications secondary to pulmonary disease, (b) in prognosis, and (c) in the assessment of permissible physical activity (to prevent overworking and consequent failure of the right ventricle induced by pulmonary hypertension).

**Differential Diagnosis of Cardiovascular Disease and Poor Physical Fitness**

The poor performance of an exercise test, by itself, does not tell whether the subject is sick or is simply unfit. Training of a cardiac patient may
indeed elicit the same physical reactions as those of sedentary but otherwise healthy subjects; intolerance to effort (dyspnoea, ECG abnormalities, etc.) may also diminish. In other words, both lack of physical fitness and cardiac disease may produce the same physiological effects, so that a poor aptitude for exercise may be due either to lack of physical training or to disease of the cardiocirculatory system. A poor exercise performance by itself cannot discriminate between these two possibilities, and is not specific evidence of a pathological state. As is often the case in chronic diseases, the effects of cardiac insufficiency and of poor physical fitness may compound one another, making it difficult to assess the real degree of invalidism.

Exercise tests do not permit differentiation between pulmonary and cardiac illnesses, or between different cardiovascular diseases. Interpretation of the results is made more difficult by differences in the degree of physical fitness between patients. Even the most specific tests may be invalidated by training. For instance, functional ECG abnormalities typical of neurocirculatory asthenia and signs of coronary insufficiency may both regress under the influence of repeated, regular muscular exercise.

Other factors that influence results are genetic characteristics, body build, environmental conditions, motivation, etc. The results should therefore be interpreted in relation to mean values for the population to which the patient belongs, taking account of the type and degree of habitual physical activity, sport activities, and physical fitness of the patient in the months preceding testing. The Swedish and German schools have tried to set up some systems for differentiating between the effects of training and of diseases, but the complexity of the equipment needed, the relative scarcity of results, and the lack of reference values make them unsuitable, so far, for general application.

**Prognostic Value of Exercise Tests**

During the past ten years some authors have suggested that the exercise ECG obtained with either the double Master test or a gradually-increasing-load test could be used, in the interests of preventive medicine or life insurance, to detect the subjects in a population who are likely, in the future, to show a high morbidity and mortality from coronary disease.

The results seem to be conclusive, particularly in the middle-aged male population and provided that the presence of an ST ischaemic response is taken as the only positive criterion. This seems the only statistically valuable index. The frequency of ST depression shows the expected increase proportional to age and to the intensity of effort; on the contrary, the frequency of T-wave abnormalities does not change with age or intensity of effort.
Value of a positive test

Subjects who show an ST change of ischaemic type during or after an exercise test seem to have a higher probability of dying from coronary disease than subjects who show no such change. The magnitude of the ischaemic ST depression during and after exercise is directly correlated with the severity of coronary disease. An ST depression of less than 0.1 mV (in maximum or near-maximum effort) corresponds to a coronary disease mortality rate twice the probable figure for the age-group in question. A depression of 0.1-0.2 mV at the same intensity of effort would bear a 5-fold increase in mortality rate, while a depression of more than 0.2 mV would bear a 20-fold increase. On the average, the probability of coronary death in subjects with ST ischaemic depression is four times higher than in subjects showing no such change. In vivo coronary arteriography confirms the association between ST changes and coronary occlusion.

Value of a negative test

As far as the Master step test is concerned, a negative result—i.e., lack of ST depression—does not exclude the presence of coronary disease. It may simply mean that, at the time of testing, the obstructive lesions of the arteries had not progressed to such a state as to cause coronary insufficiency at the relatively light effort involved. In other instances, a previously established positive response during exercise may decrease and disappear, with the development of collateral circulation and improved perfusion of the heart. In general, the Master test leads to an inadequate increase of heart rate; a treadmill test or a bicycle test, which allow gradual increase of the work-load and, consequently, progression to a higher heart rate, could disprove the negativity of a Master test. In yet other instances, a Master test may be reported as negative because the ECG is not continuously monitored during the exercise or is not monitored long enough (up to six minutes) afterwards.

The relatively limited prognostic value of the Master test as compared with other fixed-intensity tests or with progressive-loading tests (bicycle or treadmill) appears evident when the percentage frequency of ischaemic ST changes in a population clinically free from cardiovascular symptoms (males over 30 years of age) is studied. It was shown that when maximum exercises were performed by a progressive-loading test, 10% of the population sample under study showed positive ECG changes of heart ischaemia; in sub-maximum exercises the percentage of positive signs was 7%. But when the double Master test was used only 3% of the population showed ischaemic ST changes, while the standard Master test was altogether unable to elicit any significant ST depression.
Annex 1

EXERCISE TESTS IN REHABILITATION PROGRAMMES

A programme of progressive physical training has a favourable influence on the future physical fitness of the majority of patients with cardiac disease and, probably, also influences favourably the development of the disease. However, the intensity, duration and surveillance of such training programmes are not yet well defined. This is due in part to a lack of programme standardization in relation to the individual clinical conditions. As far as myocardial infarction is concerned, sufficient experience is available for certain general directions to be drawn up; for other heart conditions (congenital and valvular abnormalities, arterial hypertension, sequelae of heart surgery, etc.) the available information is still too scanty. Even in the case of myocardial infarction, however, specific problems must be individually considered.

Three stages must be considered in myocardial infarction: the acute phase, the phase of hospital care, and the convalescent phase. After the acute phase is over (i.e., when the resting ST segment has returned to normal, inflammatory signs have disappeared and symptoms are no longer present) a rehabilitation programme may be undertaken provided there are no contraindications. Proposals for such a programme have been presented by a WHO Working Group (1968).

Surveillance of training during hospitalization

During the hospital phase the exercise constitutes both treatment and test. The following parameters should be checked carefully and no further increase in effort allowed if:

1. the heart rate during exercise increases by more than 30 beats/min, or decreases by more than 10 beats/min;
2. disturbances of rhythm and of conduction appear during or immediately after exercise;
3. dyspnoea, angina or fatigue appears during or at the end of the test;
4. pallor, hypotension with bradycardia, or faintness appears.
Tests for establishing intensity of rehabilitation programme during convalescence

After three or four weeks, if the evolution of the disease seems favourable, the patient may undergo a more strenuous rehabilitation programme, either individually at home or collectively in a specialized centre. Most programmes involve rhythmic exercises (marching, cycling, etc.) of about 30 minutes' duration, repeated at least three times per week. The above-mentioned WHO Working Group (1968) proposed a progressive programme for patients recovering from myocardial infarction (between the third week and the return to work) according to whether they do or do not visit a rehabilitation centre. From time to time, starting preferably during the third or fourth week of a normal convalescence, physical fitness should be tested and the results of the fitness tests should guide the future course of participation in the programme. Heart rate is the most important and simplest guide in establishing the intensity of the exercise programme. The WHO Working Group suggested that for a constant-load exercise of 30 minutes' duration, training heart rate should not increase beyond the resting heart rate by more than 60% of the difference between the heart rate during maximum exercise and the resting heart rate. This criterion may be criticized on the grounds that a heavier load is thus imposed on elderly than on young patients. It would be better to take as the upper limit of the training heart rate: $f_{h,rest} + \frac{1}{2}(f_{h,max} - f_{h,rest})$.

Alternatively, the following limits could be imposed:

1. heart rate should not increase by more than 50% of the resting value;
2. heart rate should not increase beyond 120 beats/min or, if no severe subjective symptoms appear, beyond 150 beats/min;
3. heart rate should be no more than 70% of the difference between maximum heart rate and resting heart rate;
4. oxygen consumption should be between 60% and 70% of the aerobic power as calculated from the Åstrand nomogram;
5. oxygen requirement should not exceed 50% of the maximum aerobic power, defined here as the aerobic power that can be maintained stable for 3-5 min.

All these possible limitations to the intensity of the rehabilitation programme are rather empirical, and procedures (1) and (2) again penalize the older person. Nevertheless, most of them have been used and since the average coronary population is relatively homogeneous in respect of age they usually yield fairly comparable results. In general, the limits proposed seem safe; however, no centre has yet had experience with more than about 500 patients and there is need for further study, especially of older patients. Appearance of subjective symptoms during exercise should also be watched.
Interpretation of ECG changes varies with the investigators: some believe that ST depression of more than 0.2 mV indicates that exercise must be stopped, whereas others believe that as long as there are no symptoms of intolerance, ST depression or disturbances of rhythm should be disregarded.

Suggested sources of information concerning exercise tests in the training and rehabilitation of cardiovascular patients are: Hellerstein & Hornsten (1966); Naughton et al. (1966); Kellerman et al. (1967); König (1968); Blackburn (1969).
EXERCISE TESTS IN CHILDREN AND ADOLESCENTS

The measurement of physical effort in children and adolescents by means of exercise tests has become of increasing importance in recent years. In the fields of social paediatrics and public health, physicians are commonly faced with the problem of deciding whether the physical performance capacity of a child is adequate for his stage of development and, if it is not, of advising on a physical education programme involving sport and other forms of physical work in school as well as outside.

In the field of therapeutic medicine and particularly in the treatment of children with chronic disease, a knowledge of the development of physical ability is important. It is necessary, for instance, to determine the physical capacity of children with diabetes or obesity if one wants to adapt and direct their patterns of daily activity (Sterky, 1963). The same applies to children with serious physical handicaps (such as blindness), who are often physically inactive.

Children with congenital or acquired heart disease represent another medical field where testing of physical performance capacity can guide the physician to evaluate the effect of surgery (Adams & Duffie, 1961; Bengtsson, 1956b; Duffie & Adams, 1963).

The objective of testing programmes in children is usually to answer the following questions:

1. Does the physical performance capacity of the child under study correspond to that expected for his age-group?
2. Does the development of physical performance capacity correspond to his physical and anatomical development?
3. How does the physical performance capacity of the child relate to the standard value for young adults?

The first question may provide sociological information if a group of children should fail to meet the expected values; the second is helpful in assessing what can be expected from the individual healthy or sick child relative to his size (expressed per unit of body length or body weight) and (if performance falls outside the rather broad range of “normality”) what is necessary as a training stimulus to improve his development; and the third
provides information on whether the adolescent can be treated in the same way as an adult with respect to sports and work requirements.

Regular medical examination of schoolchildren is obligatory in many countries. In these examinations one usually obtains, in addition to the clinical findings, data on body weight and height; it was found, a long time ago, that in children without symptoms of disease functional development can be assessed rather simply from the height and body-weight increase, while the most important dimensions of the heart/lung system show an age-curve that is identical with the growth-curve (Scammon, 1930).

However, these findings are not decisive, and in school-age children the values for physical working capacity are so diverse that individual development cannot be forecast even in a group with the same body height and body weight. Because the indirect methods for the estimation of maximum oxygen uptake do not require complex equipment, these seem the best suited to regular school examinations. Such examinations are even more desirable in adolescence, and an assessment of working capacity is prescribed as part of the ILO prophylactic examination of adolescent workers. In this way a physician can decide whether the health of an adolescent would be endangered by a given type of industrial work. Decisions are too commonly based simply on measurement of body mass and on clinical examination, although such observations have only a limited bearing on the physical working capacity and maximum oxygen uptake. Measurement or prediction of the maximum oxygen uptake provides the only means of deciding what would be a tolerable work-load for an adolescent (Hubač et al., 1968).

As regards children and adolescents under physical training, ergometric methods are of great importance. Åstrand et al. (1963) showed that adolescents who are under training have a considerably higher maximum oxygen uptake than those of similar body weight but not under training. This increase in working capacity is associated with an increase of heart volume and total haemoglobin, as well as with an alteration of functional lung capacity. All these factors revert relatively quickly to previous values when training is interrupted (Eriksson et al., 1968).

Types of exercise

Exercise tests such as those proposed in Chapter 6 are commonly used in paediatrics to measure maximum oxygen uptake and related respiratory and circulatory functions.

Treadmill running has been extensively used in the exercise testing of children, and reference is made to the work of Robinson (1938), Morse et al. (1949), and Åstrand (1952). Bicycling has been used in children of 5 years and above by several investigators (Rutenfranz & Mocellin, 1968; Adams et al., 1961; Åstrand et al., 1963; Berven, 1963; Bink & Wafelbakker, 1968; Hollmann et al., 1965; Maček, 1968; Lange Andersen, 1966; Bengtsson,
Stepping has also been successfully employed by some authors (Lange Andersen, 1966). Most of these investigations are related to the age-groups from 10 to 18 years. The youngest ages where ergometric methods have been applied are 5 years on a bicycle (Rutenfranz & Mocellin, 1968) and 4 years on a treadmill (Åstrand, 1952). In order to examine children of less than 4-5 years of age, ergometer techniques have to be altered, with appropriate regard for body mass and with exact measurement of effort at quite low intensities of work (e.g., commencing at 10 kpm/min); an optical pedometer adapted to the level of a child's understanding is useful, and there is a need for greater adaptability of the saddle height and the length of the pedals. It would be useful if children's toys, such as bicycle automobiles, were converted into ergometers (Klimt, 1965) or used on a treadmill belt.

Methods of measurement

The direct measurement of maximum oxygen uptake is also easily performed in very young children. But since this approach requires a well-equipped laboratory with a specially trained staff, it is—for clinical purposes—more practical and perfectly valid to use an indirect method. It is preferable to establish the relationship between heart rate and oxygen uptake at different submaximum work-loads and to assess the maximum oxygen uptake by extrapolation to the empirically established mean value for maximum heart rate (see Chapter 8, p. 77).

As discussed in Chapter 1, the oxygen uptake values should be related to body weight or height (Åstrand, 1952; Lange Andersen, 1966; Rutenfranz & Mocellin, 1968), to total haemoglobin (Åstrand, 1952), to heart volume (Reindell et al., 1967), or to lean body mass (Parižkova, 1968). The following parameters must be determined for this purpose:

1. the regression coefficient relating heart rate and load (a);
2. the initial load (L), which must be individually selected for every child (≥ 1 W per kg body weight);
3. the corresponding pulse frequency \( f_{h,L} \);
4. the maximum pulse frequency \( f_{h,max} \) for the particular age-group; and
5. the oxygen consumption per unit of work characteristic of the ergometer and the technique used.

The indirectly measured maximum oxygen uptake is then calculated as follows (for continuously increasing effort):

\[
(\dot{V}_{O_2})_{max} = \left[ L + 60 \left( \frac{f_{h,max} - f_{h,L}}{a} \right) \right] \times K
\]

plus basal metabolic rate.
The factor 60 must be used in order to change the kpm/sec into kpm/min, because \( a \) has the dimension \( \text{min}^{-1} \)/kpm sec\(^{-1} \).

In the measurements of Mocellin & Rutenfranz (unpublished data, 1968) with continuously increasing effort, the factor \( K \) was 0.001846; this corresponds to an oxygen intake of 185 ml/100 kpm/min.

Total oxygen transport can also be calculated as \( \dot{W}_{170} \) (work rate at heart rate 170). One can obtain this in children either by graphic extrapolation of at least three constant-effort tests in a relative steady state (Wahlund, 1948; see also Fig. 22) or by calculating it from a continuously increasing effort. The calculation is similar to that for the indirect measurement of the maximum oxygen uptake (Rutenfranz, 1964):

\[
\dot{W}_{170} = L + 60 \left( \frac{f_{h, 170} - f_{h, L}}{a} \right).
\]

Unless standard techniques are used in all laboratories (see, for example, the recommendations of the International Biological Programme (IBP) working party (Shephard et al., 1968a), differences in both the directly measured and the predicted maximum oxygen consumption may occur.

The mean values for maximum oxygen uptake in some groups of children aged 10-18 years are presented in Tables 7 and 8, which show that the maximum oxygen intake (in ml \( \text{O}_2 \)/min/kg body-wt) is practically constant and independent of age between 10 and 18 years in boys, while it is smaller in girls at the beginning of puberty and decreases until the age of 15-18. The values obtained by indirect methods correspond in their magnitude and trends to those obtained by direct methods. As to \( \dot{W}_{170} \), values for one sample of

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Boys</th>
<th>Girls</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum oxygen uptake&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Maximum oxygen uptake&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>(litres/min)</td>
<td>(ml/min/kg body-wt)</td>
</tr>
<tr>
<td>9</td>
<td>1.51</td>
<td>50</td>
</tr>
<tr>
<td>11</td>
<td>1.93</td>
<td>50</td>
</tr>
<tr>
<td>13</td>
<td>2.36</td>
<td>50</td>
</tr>
<tr>
<td>15</td>
<td>3.17</td>
<td>53</td>
</tr>
<tr>
<td>17</td>
<td>3.70</td>
<td>54</td>
</tr>
</tbody>
</table>

* Data from Rutenfranz & Hettinger (1959).

1. In early childhood, maximum oxygen uptake is almost the same in boys and girls (see also Chapter 1, p. 25).
### TABLE 8. MAXIMUM OXYGEN UPTAKE* AS A FUNCTION OF AGE IN SCHOOLCHILDREN: DIRECT DETERMINATION

<table>
<thead>
<tr>
<th>Age-group (years)</th>
<th>Boston**</th>
<th>Stockholm**</th>
<th>Cologne**</th>
<th>Lapland**</th>
<th>Leiden**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>♂</td>
<td>♀</td>
<td>♂</td>
<td>♀</td>
<td>♂</td>
</tr>
<tr>
<td>10-11</td>
<td>52</td>
<td>—</td>
<td>56</td>
<td>52</td>
<td>—</td>
</tr>
<tr>
<td>12-13</td>
<td>47</td>
<td>—</td>
<td>56</td>
<td>50</td>
<td>46</td>
</tr>
<tr>
<td>14-16</td>
<td>53</td>
<td>—</td>
<td>59</td>
<td>46</td>
<td>—</td>
</tr>
<tr>
<td>16-18</td>
<td>53</td>
<td>—</td>
<td>57</td>
<td>47</td>
<td>46</td>
</tr>
</tbody>
</table>

* In ml/min/kg body-wt.

** Robinson (1938), Astrand (1962), Holmén (1963), Lange Andersen et al. (1961), Bink & Wafelbakker (1968).

Children in relation to age, body length and weight have been given by Rutenfranz & Mocellin (1968). Useful information on the assessment of physical performance capacity in children and adolescents may be found in Geubelle (1938), Howell & MacNab (1938), Mocellin & Rutenfranz (1970), and Shephard (1970).
Annex 3

EXERCISE TESTS IN POPULATION STUDIES

Exercise tests may be successfully included in many epidemiological surveys as a tool for evaluating the cardiorespiratory function, the work capacity and, in general, the physical fitness of population groups as a function of their health status and physiological characteristics. Risk factors may also be assessed through exercise testing. For instance, abnormal ECG response to exercise has proved to be a risk predictor of a high order (i.e., it has great specificity and sensitivity\(^1\)) in forecasting the possible occurrence of myocardial infarction. Abnormal ECG responses to exercise can be easily measured and may serve as an objective, although nonspecific, sign of insufficient blood flow to the heart muscle during effort. It is important to study the prevalence, incidence and distribution of these abnormalities within and between population groups, particularly in relation to health criteria and other physiological parameters.

The predictive power of exercise responses other than ECG in relation to health and disease on a population basis has not yet been thoroughly investigated. It is desirable that such studies be undertaken in the near future, that is, before the physical fitness of populations changes drastically as a result of increased urbanization and industrialization.

Intercultural comparisons are particularly needed at the present time, since many of the more interesting small and racially pure "primitive" tribes are rapidly becoming incorporated, socially and genetically, into the melting-pot of urban society. Many scientists would like to initiate longitudinal studies of the fitness of such communities as they pass from the active rural life of the hunter to the sedentary existence of the city dweller, and such studies form an important objective of the human adaptability project of the IBP. Accordingly, much of the initial effort of the IBP has been devoted to the standardization of methodology.

Some important problems that may be investigated by means of exercise tests in population surveys are the following:

1. the relationship between growth and development of physical performance;

\(^1\) For definition of sensitivity and specificity, see Rose & Blackburn (1968).
(2) the effect of aging;
(3) natural acclimatization to altitude;
(4) the effect of evolution in contrasting climates (tropical *versus* arctic, etc.);
(5) the effect of various degrees of habitual physical activity at work and during leisure time;
(6) the effect of air pollution;
(7) the effect of dietary differences (under-nutrition, over-nutrition, malnutrition);
(8) the effect of endemic diseases (parasitic or other) on the work performance; and
(9) genetically determined differences.

Some problems may be tackled by a comparative approach, e.g., by measuring and subsequently analysing data from contrasting populations, while other problems may best be studied by prospective investigations.

*Choice of exercise test*

When respiratory gas exchange is measured, any type of exercise described in this manual can be recommended, and the choice of ergometer depends upon the experience of the investigator and the type of population under study. The mechanically braked bicycle ergometer and the steps are the instruments of choice for both laboratory and field use, particularly when cost, lack of electricity and of specialized personnel for maintenance and calibration, and transportation problems are limiting factors—a situation frequently encountered in field studies in developing countries. As described in Chapter 3 and illustrated in Table 3 (see page 32), the mechanical bicycle ergometer and the steps easily fulfil most of the requirements in respect of transportation, maintenance, calibration, task familiarity, relatively low cost, and subject’s optimum performance at high \( \dot{V}_{O_2} \).

A 4- to 6-minute exercise period at submaximum work rate is recommended, since this allows measurements to be taken in the “steady state” condition. If maximum exercises are performed, the exercise should last for at least three minutes.

*Standardization of procedure*

The findings of a population survey must be reported in such a way that other investigators, even if not involved in that particular survey, may also make use of the results and compare them with other studies. This requires a carefully standardized procedure in exercise testing.

For the sake of standardization it is suggested that the basic recommendations for exercise testing as laid down in this manual be followed. Never-
theless, the individual investigator may need to prepare a protocol of his own, according to the specific requirements of the survey and taking into consideration the type and size of the population, the type of physiological parameters to be studied, the availability of funds, etc. All this would influence the choice of ergometer, the duration of the exercise, and the complexity of the test.

Instruments require careful and frequent calibration and overhauling. Access to a proper workshop is therefore important. The repeatability and validity (see Rose & Blackburn (1968) for details) should be established by each team before a population survey is conducted.

*Types of population group suitable for exercise testing*

Because of its relative complexity, exercise testing will rarely be applicable in broad population surveys. The best results will be obtained with well-defined population groups, such as schoolchildren, military personnel, athletes and occupational groups. The investigating capacity of an exercise test survey is rather limited since, if respiratory measurements are to be taken, a team of three persons cannot study more than ten subjects a day. By using a simple bicycle test with no respiratory measurements, personnel requirements may be reduced to only one well-trained technician, who can study up to 15 subjects a day. Exercise testing should therefore be restricted to only random samples or cluster samples of the population groups. Instead of the customary 3- or 4-stage testing procedure described in Fig. 22, a quicker, 2-stage procedure may be used in certain circumstances, such as when examining a large number of subjects with the simple bicycle ergometer test, the initial information obtained being used as a basis for drawing appropriately weighted subsamples for more detailed testing.

The quantity of data collected in a population study may indeed be large, and computerized data-processing becomes essential. The primary data should therefore be coded and recorded on a transfer sheet, and the information subsequently transferred to punch-cards.

The results should be reported according to the recommendations of Rose & Blackburn (1968).
EXERCISE TESTS IN ASSESSMENT OF
FITNESS FOR JOBS AND WORK ACTIVITY

The patient recovering from a severe illness will inevitably inquire about
desirable living habits for the near and more-distant future and will especially
want to know whether he will be able to resume his original work and, if
not, for what kind of work he will be eligible.

Healthy subjects may be interested in the types of sport and games for
which they can be considered as apt on the basis of their physical fitness.

Military authorities may want to make sure that their candidates for
special missions are likely to meet the physical requirements.

In all these cases, and probably in many others, it is unsatisfactory
for the medical officer to give recommendations or to formulate statements
that are built purely upon a physical examination at rest.

Submaximum tests will enable the physician to give a functional evalua­
tion of the subject's physical working capacity, and comparison with
similar data obtained in healthy subjects of the same sex, age and body build
would permit evaluation in terms of percentage of normal values. Sub­
maximum tests can also yield the necessary information for estimating
maximum oxygen uptake. However, it is the maximum tests that yield
the most valuable information on physical working capacity, in that they
allow the direct measurement of \( (V_{O_2})_{\text{max}} \).

As far as results are concerned the maximum aerobic power, directly
measured in maximum tests, and the maximum aerobic power estimated from
submaximum tests could be looked upon as being comparable, but the
accuracy is definitely lower in the submaximum measurements than in the
direct measurements. As has been indicated in Chapter 4, it may happen that
an exercise test has to be stopped because of abnormal changes in the ECG or
other pathological responses to exercise. The oxygen uptake at that level
of exercise is called the "relative maximum aerobic power"; in principle this
value could be regarded as a maximum but, unlike true maximum values, a
higher fraction of it may be accepted for prolonged efforts. It is well
established that the results of a short-lasting high-level exercise test can be
translated into terms of physical capacity for longer periods. As methods
are available for measuring the energy requirements of professional and
non-professional activities, it is now possible to match capabilities and requirements and to formulate recommendations for work and other activities on a quantitative basis.

Matching job requirements to subject's physical working capacity

In order to assess whether the work task to which an individual is exposed is properly adjusted to his physical performance capacity, or whether it is too heavy, Bonjer (1962) introduced the concept of “relative degree of loading”. This is the ratio $M_t / A_t$, where $M_t$ is the mean energy requirement for a given job during a given time “$t$”, and $A_t$ is the individual's “acceptable” oxygen consumption for the same time period. Both $M_t$ and $A_t$ are expressed as litres/min of oxygen consumption, and their determination is described in the following two sections.

(a) Energy requirements of job. Assessment of professional and non-professional physical activity should always be based on a description of the type of activities and the time involved. Such a description can be obtained by direct observation, by a diary kept by the subject himself or by inquiries made by a trained observer. The purpose is to indicate how many minutes per day are spent on activities of different energy expenditure. The sum of the products (kilocalories per minute $\times$ time in minutes for each category of activities) shows how many kilocalories are spent throughout a 24-hour period, and the average value per minute can be obtained by dividing the total by 1440. The average for 24 hours is not always the most relevant thing to study. In healthy workers it may be sufficient to know the mean professional energy expenditure ($M_p$), whereas in the case of rehabilitation of cardiac patients it seems to be of interest to take into account all activities connected with the work, including transportation, change of clothing, washing, etc.

Tables have been published that give the caloric expenditures for many different types of activity according to body weight (Passmore & Durnin, 1955; Spitzer & Hettinger, 1964). Other investigators have collected data from the literature and analysed them in terms of movements of the trunk and of the upper and lower extremities, paying attention, at the same time, to the forces to be exerted or the weights to be borne (Bink, Bonjer & Van der Sluys, 1966).

In spite of all efforts the accuracy of such assessments remains limited. To a certain extent direct measurements are preferable, but these also have their limitations. Studies of the heart rate will always suffer from the fact that not only physical activity but also the physical and psychological environment will influence the final result. Miniature tape-recorders are certainly promising for the purpose, but do not seem to be developed completely as yet, and the systems for a rapid “play-back” are extremely expensive. An event-marking system is desirable. Heart beat totalizers
have been developed recently, but they give no information about the relationship between heart rate and time.

More valuable for the assessment of energy expenditure are the measurements of oxygen uptake. Douglas bags and mechanical or electrical portable gas-meters have been used for many years, but these methods are inconvenient and for that reason the observation time is restricted. This means that many samples should be taken to eliminate variations. Face masks have proved to be less inconvenient than mouthpieces and nose-clips, and recent developments of instruments for the continuous measurement and analysis of expired air, combined with the use of masks, have solved some of the problems (Bleeker & Hoogendoorn, 1969; Bonjer, 1969). Whereas earlier studies always had to be directed to single and steady activities, it is now possible to extend the studies to longer periods of time and to follow changes in energy expenditure produced by changing activities. It is also possible to study peak loads, as, for instance, in staircase climbing. (For further details, see Bonjer, 1971).

(b) Evaluation of physical working capacity for part-time or full-time work from results of short, high-level exercise test. Physiological (\(\dot{V}_{O_2}\))\(_{max}\) and “acceptable” (\(\dot{V}_{O_2}\))\(_{max}\). For obvious reasons, the maximum level of energy expenditure over a full day’s work cannot be assessed directly for each individual by having him perform an 8-hour exercise test. It must therefore be extrapolated from the results of a standardized, short test.

It should also be borne in mind that the average level of energy expenditure, like other physiological functions, is lower the longer the working time. In other words, the mean oxygen uptake during a day’s work is expected to be a fraction of the maximum value as determined during an exercise test. Investigations carried out on large numbers of industrial workers have suggested a ratio of 3 to 1 between the maximum oxygen uptake and the “acceptable” average oxygen uptake (\(\dot{A}_{i}\)) over 8\(\frac{1}{2}\) hours. As shown in Fig. 30, the acceptable average energy expenditure of a worker (A) whose (\(\dot{V}_{O_2}\))\(_{max}\) in a short exercise test is 3.0 litres/min should be 1.3 litres/min, when considered over a 240-min (4-h) period, and 1.0 litres/min when considered over a 510-min (8\(\frac{1}{2}\)-h) period.

Over a 1440-min (24-h) period, the acceptable (\(\dot{V}_{O_2}\))\(_{max}\) would be approximately 0.6 litre/min or 2.7 kcal/min. A daily energy expenditure of 1440 \times 2.7, i.e., 3900, kcal is indeed a realistic figure for a young man doing heavy muscular work (Bonjer, 1968b).

The figures mentioned above agree with the recommendations formulated by German work physiologists (Lehmann, 1962). The proposed 3:1 ratio or 33% of the maximum oxygen uptake for 8\(\frac{1}{2}\) hours fits well with findings of Michael, Hutton & Horvath (1961), whose subjects could walk for 8 hours on a treadmill without undue fatigue if the energy cost did not exceed 35% of the maximum oxygen uptake. Åstrand (1967) found 39% in a study of
building industry workers. Fig. 30 shows that, in the case of workers B and C ($V_{O_2}^{max}$ of 2.1 and 1.8 litres/min, respectively), the $A_t$ values at 4 and 8 $\frac{1}{2}$ hours are 0.9 and 0.7 litre/min and 0.8 and 0.6 litre/min respectively.

Acceptable oxygen uptakes ($A_t$) at various working times (t) can generally be extrapolated from the graph in Fig. 30 by constructing a line in the following way: (1) plot the value for ($V_{O_2}^{max}$ obtained in a 4-min exercise

---

**FIG. 30**

ACCEPTABLE OXYGEN UPTAKE AS A FUNCTION OF WORKING TIME IN THREE SUBJECTS

At 510 minutes the acceptable oxygen uptake is one-third of the maximum oxygen uptake. *Redrawn from Bonjer (1968b).*
test \( \dot{A}_4 \) on the graph in correspondence with 4 minutes; (2) take one-third of this value and plot it in correspondence with 510 minutes \((8\frac{1}{2} \text{ hours})\); (3) connect the two points.

Alternatively, \( \dot{A}_4 \) values can be derived from the formula:

\[
\dot{A}_4 = \frac{3.76 - \log t}{3.16}.
\]

This formula was derived from the system:

\[
\dot{A}_4 = \frac{\log t - 3.756}{a}
\]

\[
a = \frac{0.602 - 2.708}{\dot{A}_4 - \frac{1}{3} \dot{A}_4}
\]

where 3.756 is the logarithm of the intercept (which is the same in all cases), "a" is the slope (negative), 0.602 is log 4 \((\text{i.e., the 4 minutes of exercise needed to determine } \dot{A}_4)\), and 2.708 is log 510 \((\text{i.e., 510 minutes } = 8\frac{1}{2} \text{ hours at which } \dot{A}_4 \text{ is } \frac{1}{3} \dot{A}_4)\).

The ratio \( M_t/\dot{A}_4 \) should never exceed unity. In the practical work situation the value should range from 0.7 to 0.9 \((\text{Bonjer, 1962})\). Analysis of values exceeding 1.0 always revealed undesirable situations. A common finding in the case of worker A in Fig. 30 would be: \( M_{510} = 0.8 \text{ litre/min}; \dot{A}_{510} = 1 \text{ litre/min}; \dot{M}_{510}/\dot{A}_{510} = 0.8 \). If worker B were to work part-time at a \( M_{240} \) of 0.8 litre/min, his relative degree of loading would be 0.8/0.9 \((= 0.89)\), whereas for the same job worker C would have to employ his full capacity at 240 minutes \((0.8/0.8 = 1)\).

**Peak loads**

Particular attention should be paid to peak loads. Maximum values are important in these cases, since there is no relation to working time. Any effort exceeding the maximum oxygen uptake and/or lasting more than four minutes will cause exhaustion and should always be avoided. Shorter and more strenuous efforts can be met by anaerobic processes, but the incidental excess of job requirements must be compensated later on by reduction of activities in the following period of time. Any excess of maximal physical working capacity must be avoided, even for short periods, if ECG changes, exceedingly high blood pressure, or other pathological responses that would call for the stopping of a usual exercise test are likely to arise. This is particularly important in the case of cardiac subjects.

**Checking correctness of recommended professional activities**

After a person has been tested for his physical capacity and the work has been analysed as to its requirements, the final success of the job placement
should always be checked even if the relative degree of loading seems to be acceptable and no peak loads are endangering the well-being of the subject. Such a check can be carried out in different ways. It may be sufficient for a patient who has returned to work after rehabilitation to see the doctor responsible for the placement periodically after completion of a working day. More sophisticated methods involve the continuous recording of the heart rate and/or ECG throughout the working day. It may be found that environmental or psychological factors play a role, which could not be foreseen during the preliminary assessments.
COMPARABILITY AND STANDARDIZATION OF EXERCISE TESTS

It is apparent from Chapters 2 and 3 that many forms of exercise test are currently used in different laboratories and in different parts of the world. This is unfortunate, because much data is collected annually, and if some measure of standardization could be achieved, interesting comparisons would be possible between groups of people differing in physical activity, diet, and other features of culture and environment in relation to health and disease.

Oxygen uptake in different types of exercise

The direct measurement of the maximum oxygen uptake provides a reference standard against which other exercise tests may be judged. Young men are quite readily pushed to their maximum aerobic power, but more difficulty is encountered in the very young, the elderly, and female subjects generally. When large-scale surveys are contemplated, the logistic requirements in terms of medical supervision become prohibitive. Nevertheless, it seems likely that within any given population there will be an adequate number of individuals who are able and willing to perform the (V\textsubscript{0\textsubscript{2}}\textsuperscript{max}) test, thereby providing a reference standard against which secondary and more widely applicable tests may be calibrated.

A comparison of maximum oxygen uptake measured in the same subjects (healthy young men) by three different types of ergometer was carried out in Toronto in 1967 by an international team of work physiologists; the data obtained are presented in Table 9 (Shephard et al., 1968a). The results show that the terminal pulse rates and arterial lactate levels two minutes after exercise are very similar for step, bicycle and treadmill exercise, but the maximum oxygen uptake in the treadmill test is 7% greater than that in the bicycle ergometer test while the step test (V\textsubscript{0\textsubscript{2}}\textsuperscript{max}) values are intermediate between the treadmill and bicycle ergometer values. Similar results have been obtained in other studies (Lange Andersen, 1968; Wyndham et al., 1966; Astrand & Saltin, 1961; Glassford et al., 1965). Comparisons on women, children, and older subjects have yet to be carried out.

The differences between the three types of exercise with regard to maximum oxygen uptake is not so great that values obtained from the three types of exercise cannot be compared; which means that any of them can be used if warranted by the circumstances of a particular experiment.
TABLE 9. MAXIMUM OXYGEN UPTAKE (MEAN, SD AND RANGE) IN THREE COMMON FORMS OF EXERCISE TEST

<table>
<thead>
<tr>
<th>Test</th>
<th>(\bar{V}\text{O}_2) max (litres/min STPD)</th>
<th>Pulse rate (beats/min)</th>
<th>Lactate level (mg/100 ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treadmill</td>
<td>3.81±0.76 (2.54–6.84)</td>
<td>190±5 (178–197)</td>
<td>122±21 (78–166)</td>
</tr>
<tr>
<td>Bicycle</td>
<td>3.56±0.71 (2.57–5.23)</td>
<td>187±9 (167–207)</td>
<td>112±15 (89–143)</td>
</tr>
<tr>
<td>Step</td>
<td>3.68±0.73 (2.06–5.59)</td>
<td>189±6 (170–195)</td>
<td>105±26 (45–166)</td>
</tr>
</tbody>
</table>

* Data from Shephard et al. (1968a), obtained on 24 healthy, young Canadian men.

However, allowance should be made for the systematic discrepancy between the treadmill and the bicycle ergometer in the interpretation of results.

The stability of an individual's \(\bar{V}_2\text{O}_2\) \(\text{max}\) for a given mode of exercise is largely a matter of good technique; however, discrepancies have sometimes been encountered in tests carried out in different laboratories (Bobbert, 1960; Bonjer, 1966; Cumming, 1968)—a fact that emphasizes the need both for a handbook of standard methodology and for a panel of approved reference laboratories where the correct technique can be mastered.

The differences in maximum oxygen uptake between step, bicycle, and treadmill exercise, although statistically significant, seem sufficiently small for interconversion of data, using appropriate scaling factors, to be contemplated. The main weakness of such a mathematical manipulation of the data is that the point of exhaustion is not the same for the steps, treadmill, and bicycle. If, for instance, performance of bicycle ergometer exercise is seriously limited by weakness of the quadriceps muscle, then the extent of the weakness—and hence the discrepancy from treadmill and step test results—may vary with the training of that muscle.

**Mechanical efficiency as a function of learning and habituation**

It is commonly held that the bicycle ergometer provides a unique method of performing a known amount of work with a constant mechanical efficiency. If this were true, it would give the bicycle ergometer an important advantage over other forms of exercise in that measurements of oxygen consumption would not be necessary for field testing.

In practice, it is hard to document this advantage. The coefficient of variation in efficiency of cycling is between 3% and 5% when experienced subjects exercise under optimum conditions, and can be as great as 8-10% in subjects who are unaccustomed to cycling (Shephard et al., 1968b); comparable figures for the step test are 5-6% in the experienced and 9-12% in the inexperienced. Although the bicycle is a little better than the step test, in both cases the prediction of oxygen intake can be made only very approximately, and oxygen consumption should be measured directly if reliable values are to be obtained.
The work performed during treadmill running cannot be measured accurately, but nomograms are available to predict the approximate oxygen cost; these are accurate to 10-14%.

There is some tendency for the efficiency of exercise to improve with repetition of all three forms of test; the change produced by a week of submaximum testing is equivalent to a 3-4% decrease in the oxygen cost of step and bicycle exercise, and a 7% decrease for treadmill exercise.

Most procedures for the interpretation of submaximum tests are based on the assumption that the pulse rate is constant at a given fraction of the individual's aerobic power. The accuracy of such procedures is thus limited by non-metabolic increases in pulse rate such as those due to anxiety.

Anxiety diminishes with repetition of the test, this being a form of negative conditioning sometimes described as habituation (Glaser, 1966; Shephard, 1966, 1967b). The greatest effect of habituation is seen on the second day of testing.

Habituation is a function of the central nervous system, and it can be difficult to distinguish from the regulatory aspects of physical training, which also lead to a decrease in pulse rate for a given submaximum workload.

Continuous and discontinuous tests

Two practical problems are posed by a series of discontinuous tests: fitness may change while the measurements are being made, and busy subjects may not be willing to return to the laboratory on the three or more occasions required for testing. Fortunately, the results obtained by a continuous test, where the load is increased every 30 seconds (or every 1 or 2 min), are closely comparable to those obtained in discontinuous exercise (Wyndham et al., 1966; Pirnay et al., 1966; Bonjer, 1966; Shephard et al., 1968a); indeed, if the correct loadings are chosen, the continuous test can be less exhausting and a slightly higher $W_{\text{max}}$ may be reached.

Subjective and practical considerations

In the case of intense effort the following considerations should be kept in mind.

Towards the end of treadmill exercise, subjects tend to complain of nausea, breathlessness and chest pain. They look intensely cyanosed, and may become unsteady on their legs, partially losing consciousness. Local pain in the legs is rarely described. On the other hand, when the bicycle ergometer is used, weakness or pain localized to the quadriceps muscle may give rise to complaint. A few subjects may report breathlessness, but the facies of circulatory exhaustion is not seen. Stepping exercise occupies a position intermediate between treadmill and bicycle exercise in this respect. Some subjects complain of weakness or pain in the leg muscles, while others are limited by dyspnoea or loss of co-ordination.
On clinical grounds, it would thus seem that treadmill exercise is limited by a central exhaustion of the cardiovascular system, while bicycle exercise is limited by fatigue of local muscle groups.

Comparative investigations on 24 young subjects (Shephard et al., 1968 a) have shown that the main complaints against the treadmill are lack of any opportunity to rest, and the need to keep in one position on the belt. Some subjects also may find the belt rather slippery. The main problem with the bicycle is saddle discomfort. A few subjects may complain of difficulty in keeping the pedal rhythm; this would probably present more of a problem to older people. Some people may feel that they would achieve a greater effort by standing on the pedals; however, body heaving of this type would seem unacceptable as a standard form of exercise. As to stepping, the 46-cm step required for maximum exercise may be found rather high by some subjects, and would probably be too difficult for older people. There is also a tendency for tripping to occur as the subjects become exhausted.

Certain other practical considerations may be noted. Complicated technical procedures such as cardiac catheterization and even the measurement of cardiac output by rebreathing methods are difficult to carry out on a running subject, and almost impossible on one who is climbing steps. Also, the selection of four, evenly spaced work-loads is rather difficult in the case of the treadmill, because the relationship between speed of walking or running and oxygen consumption is not very consistent.

Many considerations enter into the choice of an optimum exercise test. Some questions can be answered only by the individual physician concerned with the observations. Is it planned to measure the maximum oxygen uptake directly, or will a prediction be made from the response to submaximum exercise? Will extensive ancillary investigations, such as cardiac catheterization, be required? Is emergency care likely to be needed? Will tests be conducted in a well-equipped laboratory, or in a simple field station? Will a physician and trained technical staff be available at all times? Will electrical power be available?

It is obvious that with such varied requirements, one test is unlikely to meet the needs of all investigators. However, it is possible to state the ideal, and then match available tests against this criterion. The exercise should be familiar to the subject and require little skill. A difficult and unfamiliar task creates anxiety, exaggerating pulse and ventilatory responses to submaximum exercise, it also leads to rapid learning, so that it is difficult to estimate oxygen consumption from the work performed. The subject should enjoy the exercise, in order that his co-operation be ensured, and the task should not only be free from hazard but should also appear so to him. It should be easy to estimate the work performed by the subject; this implies a simple and reproducible method of calibrating the instrument, and a consistent relationship between the energy expenditure of the subject and the work performed on the machine. The loading of the apparatus
should be readily adjustable to give a nearly continuous increase of effort if desired. If used for maximum effort tests, the apparatus should be capable of driving a subject to general exhaustion rather than to local muscle fatigue. Finally, the cost should be reasonable, the noise involved in testing minimal, the maintenance requirements (including recalibration) few, and the apparatus itself compact and readily transportable.

As expected, all testing procedures present problems of various kinds and none of them can be chosen as the optimum one. The treadmill, however, despite its suitability for maximum exercise, seems the least desirable form of submaximum exercise. The apparatus is bulky, noisy, and expensive, and requires careful maintenance. The task is unfamiliar and somewhat frightening to the average subject, and in the first few days of testing the pulse rate may vary considerably with habituation (a lessening of anxiety) and learning (increased efficiency of exercise). It is not easy to select suitably spaced work-loads. The quality of the ECG is often poor, and if the condition of the subject demands rest, time is needed to transfer him to a couch. The choice for submaximum exercise thus lies between a step test and a bicycle ergometer.

The main advantages of the bicycle ergometer are (a) that variations in pulse rate due to habituation and learning are slight, and (b) the subject's arms are relatively immobile, thus permitting such procedures as blood pressure measurement and catheterization of the arm vessels to be carried out. The mechanical efficiency of effort can also be more precisely determined than for other types of effort. On the other hand, careful calibration is essential in order to measure the work performed, and a good quality bicycle ergometer is relatively expensive. The ECG may be distorted by muscle noise, and it is not always easy for a subject encumbered by leads to dismount in an emergency.

A 23-cm step is familiar to most subjects, but some anxiety may arise from tripping at rapid rates of ascent. The apparatus is cheap and portable, and requires no maintenance, calibration or electricity supply. The intensity of exercise is readily altered by a simple adjustment of the metronome setting. Anaerobic work is minimal. The mechanical efficiency of effort is a little more variable than on the bicycle ergometer, but if care is taken to ensure complete ascent and descent, the work performed can be estimated from the step height and body weight with reasonable accuracy. The main disadvantage of the step test is that it involves a continuous movement of the arms and head, and this creates difficulties in the making of certain physiological measurements.

It is difficult to propose a single test that is suited to the needs of every experimental situation. In the field situation, there is much to commend a simple stepping procedure, but a bicycle ergometer should be employed if it is necessary to measure blood pressure or to carry out vascular catheterization.
### Annex 6

**SPECIALIZED TERMS AND UNITS USED IN EXERCISE TESTING***

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Dimension</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>—</td>
<td>Arterial (subscript)</td>
</tr>
<tr>
<td>A</td>
<td>%; ml/litre</td>
<td>Alveolar (subscript)</td>
</tr>
<tr>
<td>C</td>
<td>ml/100 ml or ml/litre</td>
<td>Gas concentration</td>
</tr>
<tr>
<td>$C_{a,O_2} - C_{v,O_2}$</td>
<td>ml/100 ml</td>
<td>Arteriovenous oxygen difference</td>
</tr>
<tr>
<td>$C_v,O_2$</td>
<td>ml/100 ml</td>
<td>Mean concentration of oxygen in mixed venous blood</td>
</tr>
<tr>
<td>D</td>
<td>ml/min/mm Hg; (^a)</td>
<td>Diffusing capacity</td>
</tr>
<tr>
<td>D(_L)</td>
<td>ml/min/mm Hg; (^a)</td>
<td>Lung diffusing capacity</td>
</tr>
<tr>
<td>D(_L,O_2)</td>
<td>ml/min/mm Hg; (^a)</td>
<td>Lung diffusing capacity for oxygen</td>
</tr>
<tr>
<td>D(_L,CO_2)</td>
<td>ml/min/mm Hg; (^a)</td>
<td>Lung diffusing capacity for carbon dioxide</td>
</tr>
<tr>
<td>D(_m)</td>
<td>ml/min/mm Hg; (^a)</td>
<td>Diffusing capacity of alveolar capillary membrane</td>
</tr>
<tr>
<td>D(_O_2)</td>
<td>ml/min/mm Hg; (^a)</td>
<td>Diffusing capacity for oxygen</td>
</tr>
<tr>
<td>D(_t)</td>
<td>ml/min/mm Hg; (^a)</td>
<td>Tissue diffusing capacity</td>
</tr>
<tr>
<td>E</td>
<td>—</td>
<td>Expired (subscript)</td>
</tr>
<tr>
<td>f(_R)</td>
<td>breaths/min</td>
<td>Respiratory rate (breathing frequency)</td>
</tr>
<tr>
<td>F(_E)</td>
<td>%</td>
<td>Fraction of expired gas</td>
</tr>
<tr>
<td>F(_I)</td>
<td>%</td>
<td>Fraction of inspired gas</td>
</tr>
</tbody>
</table>

* A dot over a symbol indicates that it refers to a time derivative.

\(^a\) The traditional units of the physiologist are ml/min/mm Hg. However, in order to be dimensionally equivalent to alveolar ventilation and cardiac output, diffusion should be expressed as ml/min per ml/litre concentration gradient (i.e., litres/mm).
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Dimension</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{FEV}_{1.0} )</td>
<td>litres</td>
<td>Forced expiratory volume in one second</td>
</tr>
<tr>
<td>FRC</td>
<td>litres</td>
<td>Functional residual capacity</td>
</tr>
<tr>
<td>FVC</td>
<td>litres</td>
<td>Forced vital capacity</td>
</tr>
<tr>
<td>( \text{I} )</td>
<td>—</td>
<td>Inspired (subscript)</td>
</tr>
<tr>
<td>( \text{MC} )</td>
<td>litres</td>
<td>Pulmonary mid-capacity</td>
</tr>
<tr>
<td>( \text{MMV} )</td>
<td>litres</td>
<td>Maximum minute ventilation</td>
</tr>
<tr>
<td>( \text{MVV} )</td>
<td>litres/min</td>
<td>Maximum voluntary ventilation</td>
</tr>
<tr>
<td>( \text{MVV}_{100} )</td>
<td>litres/min</td>
<td>Maximum voluntary ventilation at 100 breaths/min</td>
</tr>
<tr>
<td>( \text{P} )</td>
<td>mm Hg</td>
<td>Tension (partial pressure) of gas</td>
</tr>
<tr>
<td>( \text{P}_{a,\text{CO}_2} )</td>
<td>mm Hg</td>
<td>Arterial carbon dioxide pressure</td>
</tr>
<tr>
<td>( \text{P}_{a,\text{O}_2} )</td>
<td>mm Hg</td>
<td>Arterial oxygen pressure</td>
</tr>
<tr>
<td>( \text{P}_{A,\text{CO}_2} )</td>
<td>mm Hg</td>
<td>Alveolar carbon dioxide pressure</td>
</tr>
<tr>
<td>( \text{P}_{E,\text{CO}_2} )</td>
<td>mm Hg</td>
<td>Tension of expired carbon dioxide</td>
</tr>
<tr>
<td>( \text{PEF} )</td>
<td>litres/min</td>
<td>Peak expiratory flow</td>
</tr>
<tr>
<td>( \text{P}_{i,\text{O}_2} )</td>
<td>mm Hg</td>
<td>Tension of inspired oxygen</td>
</tr>
<tr>
<td>( \text{R} )</td>
<td>—</td>
<td>Gas exchange ratio (respiratory quotient)</td>
</tr>
<tr>
<td>( \text{RE}_{O_2} )</td>
<td>—</td>
<td>Respiratory (ventilatory) equivalent for oxygen</td>
</tr>
<tr>
<td>( \text{S}_{a,\text{O}_2} )</td>
<td>%</td>
<td>Oxygen saturation of arterial blood</td>
</tr>
<tr>
<td>( \text{TLC} )</td>
<td>litres</td>
<td>Total lung capacity</td>
</tr>
<tr>
<td>( \text{TLV} )</td>
<td>litres</td>
<td>Total lung volume</td>
</tr>
<tr>
<td>( \text{UO}_2 )</td>
<td>litres/min</td>
<td>Transfer coefficient for oxygen uptake</td>
</tr>
<tr>
<td>( \text{v} )</td>
<td>—</td>
<td>Venous (subscript)</td>
</tr>
<tr>
<td>( \dot{\text{v}} )</td>
<td>litres/min</td>
<td>Pulmonary ventilation</td>
</tr>
<tr>
<td>( \dot{\text{v}}_A )</td>
<td>litres/min</td>
<td>Alveolar ventilation</td>
</tr>
<tr>
<td>( \text{v}_e )</td>
<td>ml</td>
<td>Volume of blood in alveolar capillaries</td>
</tr>
<tr>
<td>( \text{VC} )</td>
<td>litres</td>
<td>Vital capacity</td>
</tr>
<tr>
<td>( \text{V}_E )</td>
<td>litres</td>
<td>Volume of expired air</td>
</tr>
<tr>
<td>( \dot{\text{V}}_E )</td>
<td>litres/min</td>
<td>Expiratory minute volume</td>
</tr>
<tr>
<td>( \text{V}_{\text{max}} )</td>
<td>litres/min</td>
<td>Pulmonary ventilation during exhaustive muscular effort</td>
</tr>
<tr>
<td>( \dot{\text{V}}_{O_2} )</td>
<td>litres/min</td>
<td>Oxygen uptake</td>
</tr>
<tr>
<td>( \dot{\text{V}}_{O_2,\text{max}} )</td>
<td>litres/min</td>
<td>Maximum oxygen uptake</td>
</tr>
<tr>
<td>( \dot{\text{V}}_{O_2,170} )</td>
<td>litres/min</td>
<td>Oxygen uptake at heart rate 170</td>
</tr>
<tr>
<td>( \dot{\text{V}}_{O_2,900} )</td>
<td>litres/min</td>
<td>Oxygen uptake at specified workload (e.g., 900 kpm/min)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Dimension</td>
<td>Definition</td>
</tr>
<tr>
<td>----------</td>
<td>-----------</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>RESPIRATION</strong> <em>(continued)</em></td>
</tr>
<tr>
<td>$V_T$</td>
<td>$\text{ml}$</td>
<td>Tidal volume</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>—</td>
<td>Air/blood partition coefficient</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>CIRCULATION</strong></td>
</tr>
<tr>
<td>BP</td>
<td>mm Hg</td>
<td>Blood pressure</td>
</tr>
<tr>
<td>CI</td>
<td>litres/min/m$^2$</td>
<td>Cardiac index</td>
</tr>
<tr>
<td>D</td>
<td>—</td>
<td>Diastolic (subscript)</td>
</tr>
<tr>
<td>$f_h$</td>
<td>beats/min</td>
<td>Heart rate</td>
</tr>
<tr>
<td>$f_{h,900}$</td>
<td>beats/min</td>
<td>Heart rate at specified work-load (e.g., 900 kpm/min)</td>
</tr>
<tr>
<td>$f_{h,2.10}$</td>
<td>beats/min</td>
<td>Heart rate at specified oxygen uptake (e.g., 2.10 litres/min)</td>
</tr>
<tr>
<td>LPI</td>
<td>ml/beat; kpm/beat</td>
<td><em>Leistungspulsindex</em> (oxygen pulse)</td>
</tr>
<tr>
<td>$\bar{P}$</td>
<td>mm Hg</td>
<td>Mean pressure</td>
</tr>
<tr>
<td>$\bar{P}_c$</td>
<td>mm Hg</td>
<td>Mean capillary pressure</td>
</tr>
<tr>
<td>$P_{D,a}$</td>
<td>mm Hg</td>
<td>Diastolic pressure, arterial</td>
</tr>
<tr>
<td>$P_{D,ao}$</td>
<td>mm Hg</td>
<td>Diastolic pressure, aortic</td>
</tr>
<tr>
<td>$P_{D,p}$</td>
<td>mm Hg</td>
<td>Diastolic-pressure, pulmonary</td>
</tr>
<tr>
<td>$P_{s,a}$</td>
<td>mm Hg</td>
<td>Systolic pressure, arterial</td>
</tr>
<tr>
<td>$P_{s,ao}$</td>
<td>mm Hg</td>
<td>Systolic pressure, aortic</td>
</tr>
<tr>
<td>$P_{s,p}$</td>
<td>mm Hg</td>
<td>Systolic pressure, pulmonary</td>
</tr>
<tr>
<td>$Q$</td>
<td>litres/min</td>
<td>Cardiac output</td>
</tr>
<tr>
<td>$Q_o$</td>
<td>ml/min</td>
<td>Pulmonary capillary flow</td>
</tr>
<tr>
<td>$Q_s$</td>
<td>ml</td>
<td>Stroke volume</td>
</tr>
<tr>
<td>R</td>
<td>dynes sec/cm$^2$; mm Hg/ml/min</td>
<td>Vascular resistance</td>
</tr>
<tr>
<td>$S$</td>
<td>—</td>
<td>Systolic (subscript)</td>
</tr>
<tr>
<td>SI</td>
<td>ml/stroke/m$^2$</td>
<td>Systolic index</td>
</tr>
<tr>
<td>$V_h$</td>
<td>ml</td>
<td>Heart volume</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>WORK</strong></td>
</tr>
<tr>
<td>$\text{kgm}^*$</td>
<td></td>
<td>kilogram-metre</td>
</tr>
<tr>
<td>$\text{kpm}^*$</td>
<td></td>
<td>kilopond-metre</td>
</tr>
<tr>
<td>$W^*$</td>
<td>kpm/min; watts</td>
<td>watt (also symbol for “Work”)</td>
</tr>
<tr>
<td>$W$</td>
<td>—</td>
<td>Work rate</td>
</tr>
</tbody>
</table>

* The relationship between the various units of power and work is explained in Chapter 8.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Dimension</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W_{2.10} )</td>
<td>kpm/min; watts</td>
<td>Work rate at a specified oxygen uptake (e.g., 2.10 litres/min)</td>
</tr>
<tr>
<td>( W_{170} )</td>
<td>kpm/min; watts</td>
<td>Work rate at a heart rate of 170</td>
</tr>
<tr>
<td>( W_h )</td>
<td>mm Hg x beats/min</td>
<td>Work of the heart</td>
</tr>
<tr>
<td>( W_{\text{max}} )</td>
<td>kpm/min; watts</td>
<td>Maximum work rate</td>
</tr>
<tr>
<td>( W_l )</td>
<td>kpm/min; watts</td>
<td>Work of left ventricle</td>
</tr>
<tr>
<td>( W_t )</td>
<td>kpm</td>
<td>Total work performed in time “t”</td>
</tr>
</tbody>
</table>

**OTHER TERMS AND UNITS**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Dimension</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATPS</td>
<td>—</td>
<td>Ambient temperature and pressure, saturated with vapour</td>
</tr>
<tr>
<td>BTPS</td>
<td>—</td>
<td>Body temperature and pressure, saturated with vapour</td>
</tr>
<tr>
<td>BSA</td>
<td>m²</td>
<td>Body surface area</td>
</tr>
<tr>
<td>BV</td>
<td>litres</td>
<td>Blood volume</td>
</tr>
<tr>
<td>BW</td>
<td>kg</td>
<td>Body weight</td>
</tr>
<tr>
<td>CBV</td>
<td>litres</td>
<td>Central blood volume</td>
</tr>
<tr>
<td>ECG</td>
<td>—</td>
<td>Electrocardiogram</td>
</tr>
<tr>
<td>H</td>
<td>cm</td>
<td>Height</td>
</tr>
<tr>
<td>Hb</td>
<td>—</td>
<td>Haemoglobin</td>
</tr>
<tr>
<td>Hc</td>
<td>%</td>
<td>Haematocrit</td>
</tr>
<tr>
<td>LBM</td>
<td>kg</td>
<td>Lean body mass</td>
</tr>
<tr>
<td>Met</td>
<td>—</td>
<td>Ratio of MR to basal metabolic rate</td>
</tr>
<tr>
<td>MR</td>
<td>kcal/min</td>
<td>Metabolic rate</td>
</tr>
<tr>
<td>MU</td>
<td>—</td>
<td>Metabolic units</td>
</tr>
<tr>
<td>NOT</td>
<td>kg</td>
<td>Non-obesity tissue</td>
</tr>
<tr>
<td>PV</td>
<td>litres</td>
<td>Plasma volume</td>
</tr>
<tr>
<td>RCV</td>
<td>ml</td>
<td>Red cell volume</td>
</tr>
<tr>
<td>STPD</td>
<td>—</td>
<td>Standard temperature and pressure, dry gas</td>
</tr>
<tr>
<td>T</td>
<td>°C</td>
<td>Temperature</td>
</tr>
<tr>
<td>T_r</td>
<td>°C</td>
<td>Rectal temperature</td>
</tr>
<tr>
<td>T_s</td>
<td>°C</td>
<td>Skin temperature</td>
</tr>
<tr>
<td>T_{r-s}</td>
<td>°C</td>
<td>Rectal-skin temperature gradient</td>
</tr>
<tr>
<td>TBV</td>
<td>litres</td>
<td>Total blood volume</td>
</tr>
</tbody>
</table>
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