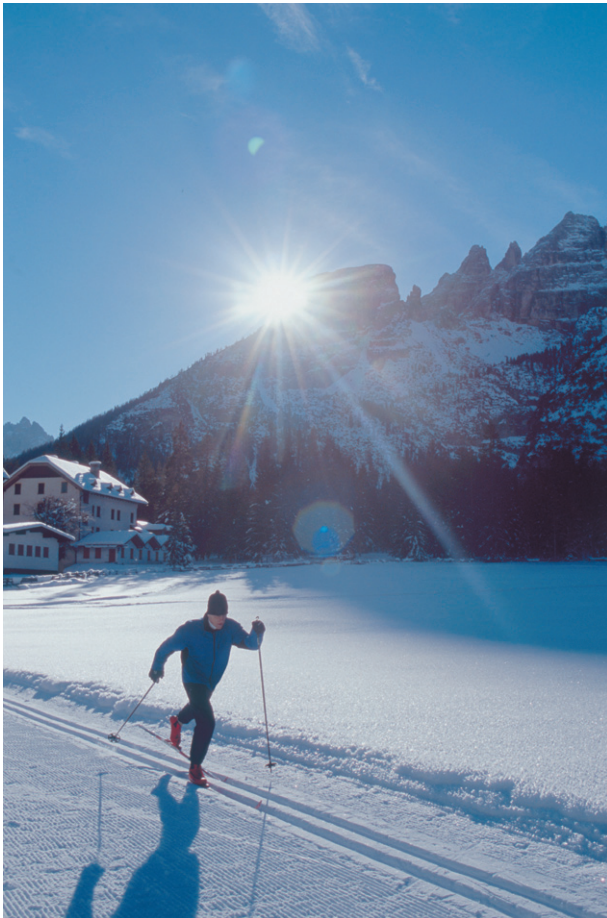Chapter 13

Cardiovascular Responses to Exercise

After studying the chapter, you should be able to

- Graph and explain the pattern of response for the major cardiovascular variables during short-term, light to moderate submaximal aerobic exercise.

- Graph and explain the pattern of response for the major cardiovascular variables during long-term, moderate to heavy submaximal aerobic exercise.

- Graph and explain the pattern of response for the major cardiovascular variables during incremental aerobic exercise to maximum.

- Graph and explain the pattern of response for the major cardiovascular variables during dynamic resistance exercise.

- Graph and explain the pattern of response for the major cardiovascular variables during static exercise.

- Compare and contrast the response of the major cardiovascular variables to short-term, light to moderate submaximal aerobic exercise; incremental aerobic exercise to maximum; dynamic resistance exercise; and static exercise.

- Discuss the similarities and differences between the sexes in the cardiovascular response to the various classifications of exercise.

- Discuss the similarities and differences between young and middle-aged adults in the cardiovascular response to the various classifications of exercise.

Introduction

All types of human movement, no matter what the mode, duration, intensity, or pattern, require an expenditure of energy above resting values. Much of this energy will be provided through the use of oxygen. In order to supply the working muscles with the needed oxygen, the cardiovascular and respiratory systems must work together. The response of the respiratory system during exercise was detailed in Chapter 11. This chapter describes the parallel cardiovascular responses to dynamic aerobic activity, static exercise, and dynamic resistance exercise.

Cardiovascular Responses to Aerobic Exercise

Aerobic exercise requires more energy—and, hence, more oxygen (and thus the use of the term *aerobic,* with oxygen)—than either static or dynamic resistance exercise. How much oxygen is needed depends primarily on the intensity at which the activity is performed and secondarily on the duration of the activity. Like the discussion on respiration, this discussion will categorize the exercises performed as being short-term (5–10 min), light (30–49% of maximal oxygen consumption, $\dot{V}O_2max$) to moderate (50–74% of $\dot{V}O_2max$) submaximal exercise; long-term (greater than 30 min), moderate to heavy submaximal (60–85% of $\dot{V}O_2max$) exercise; or incremental exercise to maximum, increasing from ~30% to 100% of $\dot{V}O_2max$.

Short-Term, Light to Moderate Submaximal Aerobic Exercise

At the onset of short-term, light- to moderate-intensity exercise, there is an initial increase in cardiac output ($\dot{Q}$) to a plateau at steady state (see Figure 13.1a). Cardiac output plateaus within the first 2 min of exercise, reflecting the fact that cardiac output is sufficient to transport the oxygen needed to support the metabolic demands (ATP production) of the activity. Cardiac output increases owing to an initial increase in both stroke volume (SV) (Figure 13.1b) and heart rate (HR) (Figure 13.1c). Both variables level off within 2 min.

During exercise of this intensity the cardiorespiratory system is able to meet the metabolic demands of the body; thus, the term **steady state** or steady rate

> **Steady State** A condition in which the energy expenditure provided during exercise is balanced with the energy required to perform that exercise and factors responsible for the provision of this energy reach elevated levels of equilibrium.

is often used to describe this type of exercise. During steady state exercise, the exercise is performed at an intensity such that energy expenditure is balanced with the energy required to perform the exercise. The plateau evidenced by the cardiovascular variables (in Figure 13.1) indicates that a steady state has been achieved.

The increase in stroke volume results from an increase in venous return, which, in turn, increases the left ventricular end–diastolic volume (LVEDV) (preload). The increased preload stretches the myocardium and causes it to contract more forcibly in accordance with the Frank-Starling law of the heart described in Chapter 12. Contractility of the myocardium is also enhanced by the sympathetic nervous system, which is activated during physical activity. Thus, an increase in the left ventricular end–diastolic volume and a decrease in the left ventricular end–systolic volume (LVESV) account for the increase in stroke volume during light to moderate dynamic exercise (Poliner, et al., 1980). Heart rate increases immediately at the onset of activity as a result of parasympathetic withdrawal. As exercise continues, further increases in heart rate are due to the action of the sympathetic nervous system (Rowell, 1986).

Systolic blood pressure (SBP) will rise in a pattern very similar to that of cardiac output: There is an initial increase and a plateau once steady state is achieved (Figure 13.1d). The increase in systolic blood pressure is brought about by the increase in cardiac output. Systolic blood pressure would be even higher if not for the fact that resistance decreases, thereby partially offsetting the increase in cardiac output. When blood pressure (BP) is measured intra-arterially, diastolic blood pressure (DBP) does not change. When it is measured by auscultation it either does not change or may go down slightly. Diastolic blood pressure remains relatively constant because of peripheral vasodilation, which facilitates blood flow to the working muscles. The small rise in systolic blood pressure and the lack of a significant change in diastolic blood pressure cause the mean arterial pressure (MAP) to rise only slightly, following the pattern of systolic blood pressure.

Total peripheral resistance (TPR) decreases owing to vasodilation in the active muscles (Figure 13.1e). The vasodilation of vessels in the active muscles is brought about primarily by the influence of local chemical factors (lactate, K^+, and so on), which reflect increased metabolism. The decrease in TPR can be calculated using Equation 12.8:
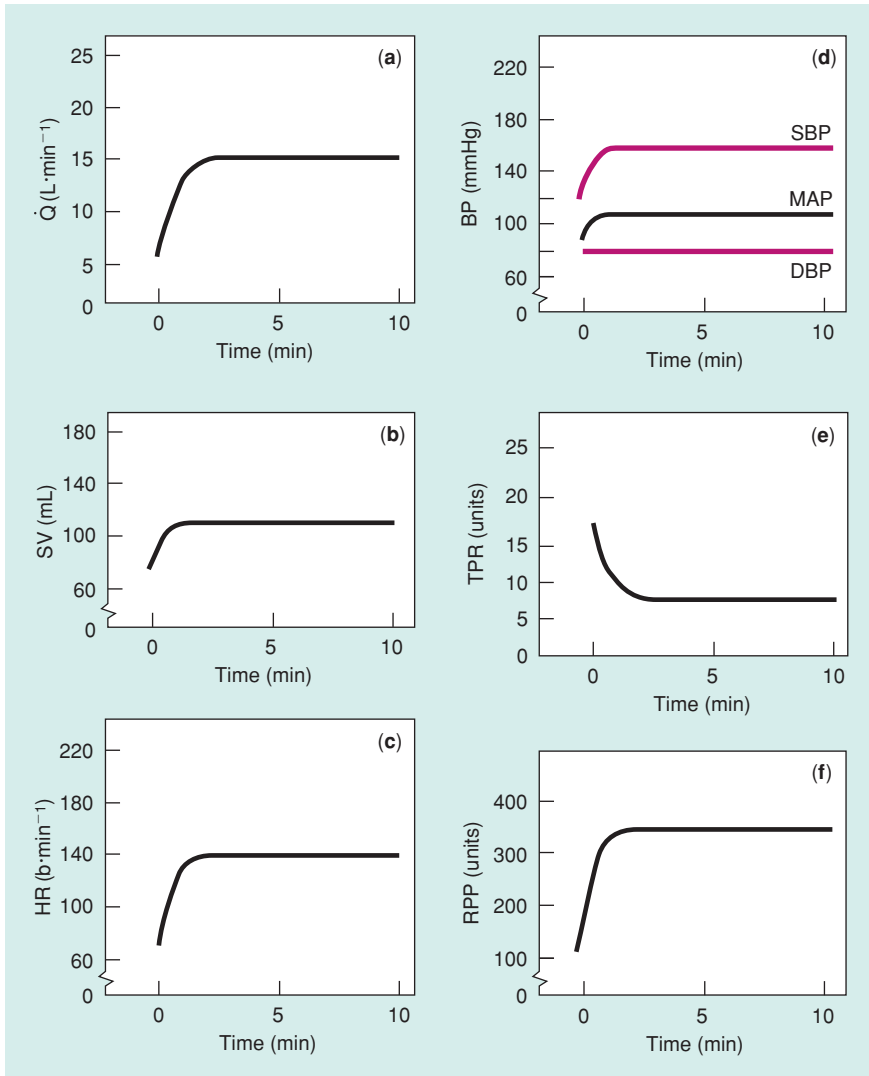
$$TPR = \frac{MAP}{\dot{Q}}$$

Figure 13.1
Cardiovascular Responses to Short-Term, Light to Moderate Aerobic Exercise

Example

Calculate TPR by using the following information from Figures 13.1a and 13.1d:

$$MAP = 110 \text{ mmHg} \qquad \dot{Q} = 15 \text{ L·min}^{-1}$$

The computation is

$$TPR = \frac{110 \text{ mmHg}}{15 \text{ L·min}^{-1}} = 7.33 \text{ (TPR units)}$$

Thus, TPR is 7.33 for light dynamic exercise. ✛

The decrease in total peripheral resistance has two important implications. First, the vasodilation in the active muscle that causes the decrease in resistance has the effect of increasing blood flow to the active muscle, thereby increasing the availability of oxygen and nutrients. Second, the decrease in resistance keeps mean arterial pressure from increasing dramatically. The increase in mean arterial pressure is determined by the relative changes in cardiac output and total peripheral resistance. Since cardiac output increases more than resistance decreases, mean arterial pressure increases slightly during dynamic exercise. However, the increase in mean arterial pressure would be much greater if resistance did not decrease.

Myocardial oxygen consumption increases during dynamic aerobic exercise because the heart must do more work to pump an increased cardiac output to the working muscles. The rate-pressure product will increase in relation to increases in heart rate and systolic blood pressure, reflecting the greater myocardial oxygen demand of the heart during exercise (Figure 13.1f). The Question of Understanding box on page 354 provides an example of normal responses to exercise. Refer back to it as each category of exercise is discussed and check your answers in Appendix D.

The actual magnitude of the change for each of the variables shown in Figure 13.1 depends on the

A Question of Understanding

The following measurements were obtained on a 42-year-old man at rest and during light aerobic exercise, during heavy aerobic exercise, during maximal dynamic aerobic exercise, and during sustained static contractions at 50% MVC.

Condition	HR (b·min^{-1})	SBP (mmHg)	DBP (mmHg)	$\dot{Q}$ (L·min^{-1})
Rest	80	134	86	6
Light aerobic	130	150	86	10
Heavy aerobic	155	170	88	13
Maximal aerobic	180	200	88	15
Sustained static	135	210	100	8

Calculate MAP, TPR, and RPP for each condition.

Figure 13.2

Percent Reduction of Plasma Volume during 30-min Moderate Bicycle Exercise to Maximum

workload, environmental conditions, and the genetic makeup and fitness level of the individual.

Blood volume decreases during dynamic aerobic exercise. Figure 13.2 shows the percent reduction of plasma volume during 30 min of moderate bicycle exercise (60–70% $\dot{V}O_2$max) in a warm environment (Fortney, et al., 1981). The largest changes occur during the first 5 min of exercise, which is consistent with short-term exercise. Following the initial rapid decrease, plasma volume stabilizes. This rapid decrease in plasma volume suggests that it is fluid shifts, rather than fluid loss, that accounts for the initial decrease in plasma volume (Wade and Freund, 1990). The magnitude of the decrease in plasma volume is dependent upon the intensity of exercise, environmental factors, and the hydration status of the individual.

Figure 13.3 illustrates the distribution of cardiac output at rest and during light exercise. Notice that cardiac output increases from 5.8 L·min^{-1} to 9.4 L·min^{-1} in this example (the increase in $\dot{Q}$ is illustrated by the increased size of the pie chart). The most dramatic change in cardiac output distribution with light exercise is the increased percentage (47%) and the actual amount of blood flow (4500 mL) that is directed to the working muscles. Skin blood flow also increases to meet the thermoregulatory demands of exercise. The absolute amount of blood flow to the coronary muscle also increases although the percentage of cardiac output remains relatively constant. The absolute amount of cerebral blood flow remains constant, which means that the percentage of cardiac output distributed to the brain decreases. Both renal and splanchnic blood flow are modestly decreased during light exercise.
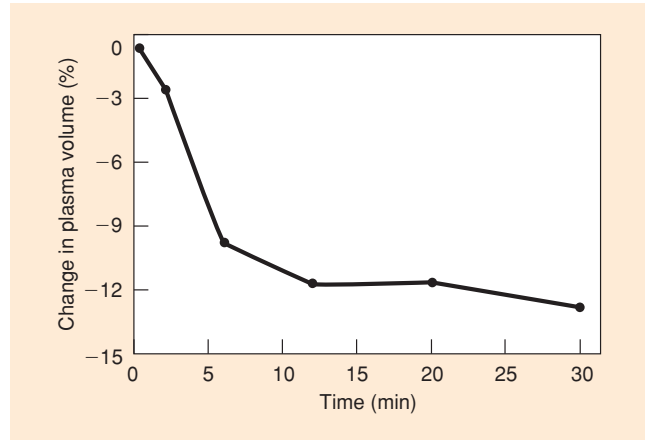
Long-Term, Moderate to Heavy Submaximal Aerobic Exercise

The cardiovascular responses to long-term, moderate to heavy exercise (60–85% of $\dot{V}O_2$max) are shown in Figure 13.4. As for light to moderate workloads, cardiac output increases rapidly during the first minutes of exercise and then plateaus and is maintained at a relatively constant level throughout exercise (Figure 13.4a). Notice, however, that the absolute cardiac output attained is higher during heavy exercise than it was during light to moderate exercise. The initial increase in cardiac output is brought about by an increase in both stroke volume and heart rate.

Stroke volume exhibits a pattern of initial increase, plateaus, and then displays a negative (downward) drift. Stroke volume increases rapidly during the first minutes of exercise and plateaus at a maximal level after a workload of approximately 40–50% of $\dot{V}O_2$max has been achieved (P. Åstrand, et al., 1964) (Figure 13.4b). Thus, during work that requires more than 50% of $\dot{V}O_2$max, the stroke volume response is not intensity dependent. Stroke volume remains relatively constant during the first 30 min of heavy exercise.

As for light to moderate exercise, the increase in stroke volume results from an increased venous return, leading to the Frank-Starling mechanism, and increased contractility owing to sympathetic nerve
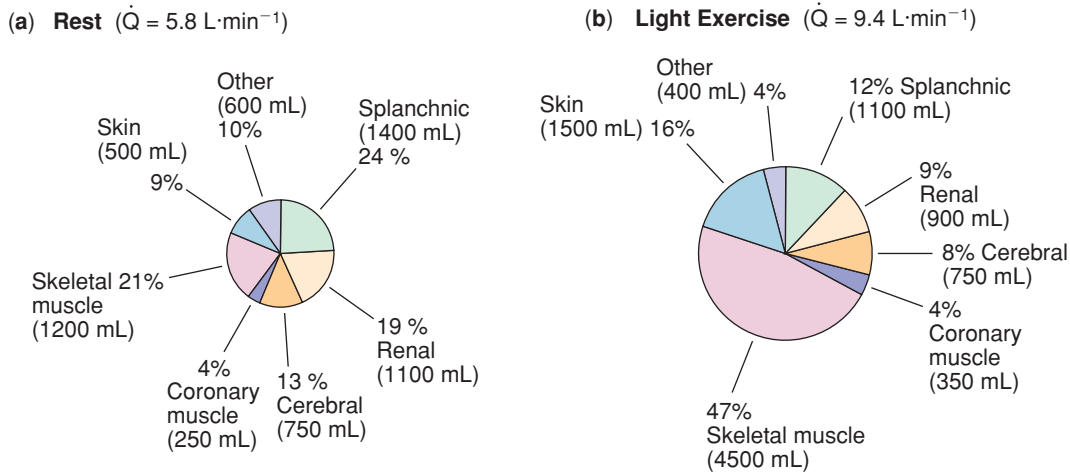
(a) Rest $(\dot{Q} = 5.8 \text{ L·min}^{-1})$

Other
(600 mL)
10%

Skin
(500 mL)
9%

Splanchnic
(1400 mL)
24 %

Skeletal 21%
muscle
(1200 mL)

19 %
Renal
(1100 mL)

4%
Coronary
muscle
(250 mL)

13 %
Cerebral
(750 mL)

(b) Light Exercise $(\dot{Q} = 9.4 \text{ L·min}^{-1})$

Other
(400 mL) 4%

12% Splanchnic
(1100 mL)

Skin
(1500 mL) 16%

9%
Renal
(900 mL)

8% Cerebral
(750 mL)

4%
Coronary
muscle
(350 mL)

47%
Skeletal muscle
(4500 mL)

Figure 13.3
Distribution of Cardiac Output at Rest and during Light Exercise
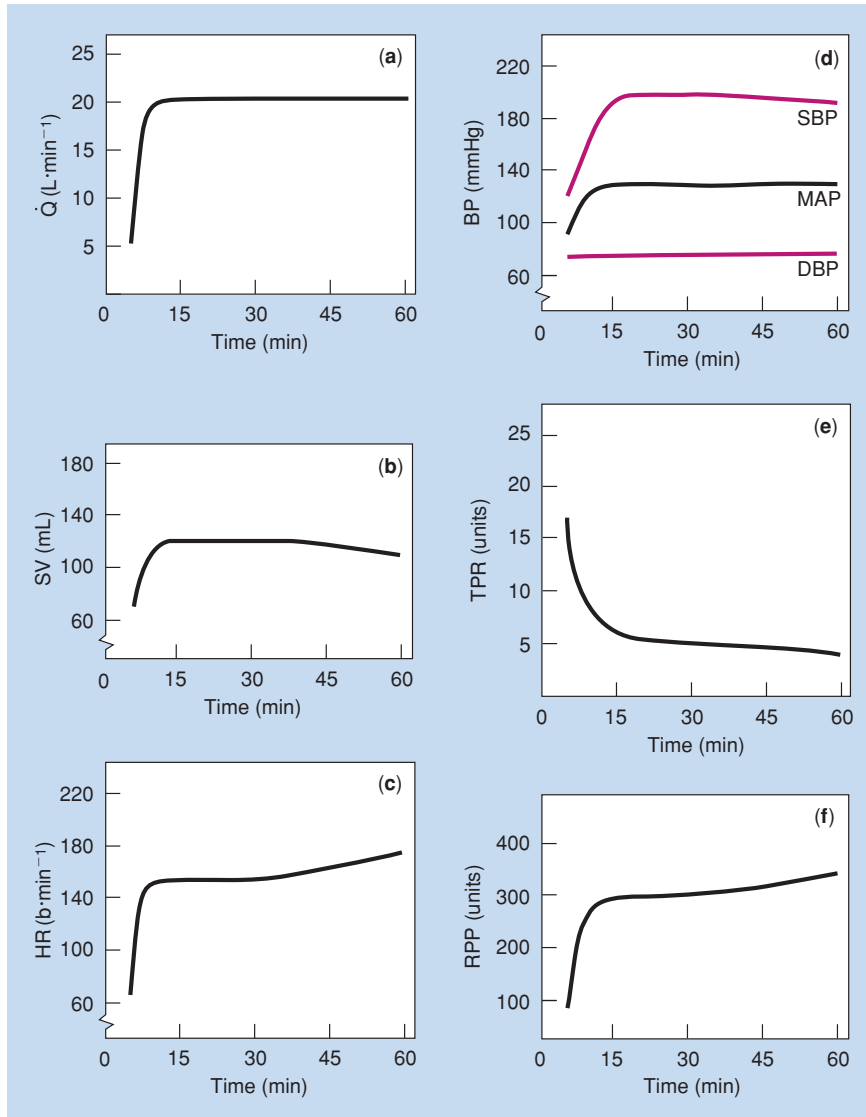
Source: Data from Anderson (1968).

Figure 13.4
Cardiovascular Responses to Long-Term, Moderate to Heavy Submaximal Aerobic Exercise

stimulation. Thus, changes in stroke volume occur because left ventricular end–diastolic volume increases and left ventricular end–systolic volume decreases (Poliner, et al., 1980). Left ventricular end–diastolic volume increases because of the return of blood to the heart by the active muscle pump, increased venoconstriction (which decreases venous pooling, thereby increasing venous return), and increased cardiac output. Left ventricular end–systolic volume decreases owing to augmented contractility of the heart, which effectively ejects more blood from the ventricle, leaving a smaller residual volume.

However, if exercise continues beyond approximately 30 min, stroke volume gradually drifts downward although it remains elevated above resting values. The downward shift in stroke volume after approximately 30 min is most likely due to thermoregulatory stress; plasma loss and a redirection of blood to the cutaneous vessels in an attempt to dissipate heat (Rowell, 1986). This effectively reduces venous return and thus causes the reduction in stroke volume.

Heart rate displays a pattern of initial increase, plateaus at steady state, and then shows a positive drift. Heart rate increases sharply during the first 1–2 min of exercise, with the magnitude of the increase depending on the intensity of exercise (Figure 13.4c). The increase in heart rate is brought about by parasympathetic withdrawal and activation of the sympathetic nervous system. After approximately 30 min of heavy exercise heart rate begins to drift upward. The increase in heart rate is proportional to the decrease in stroke volume, so cardiac output is maintained during exercise.

The changes observed in cardiovascular variables, notably in heart rate and stroke volume, during prolonged, heavy submaximal exercise without a change in workload are known as **cardiovascular drift.** Cardiovascular drift is probably associated with rising body temperature during prolonged exercise. The combination of exercise and heat stress produces competing regulatory demands—specifically, competition between skin and muscle for large fractions of cardiac output. Stroke volume decreases as a result of vasodilation, a progressive increase in the fraction of blood being directed to the skin in an attempt to dissipate heat from the body, and a loss of plasma volume (Rowell, 1974; Sjogaard, et al., 1988).

The magnitude of cardiovascular drift is heavily influenced by fluid ingestion. Figure 13.5 presents data from a study in which subjects cycled for 2 hr with and without fluid replacement (Hamilton, et al.,
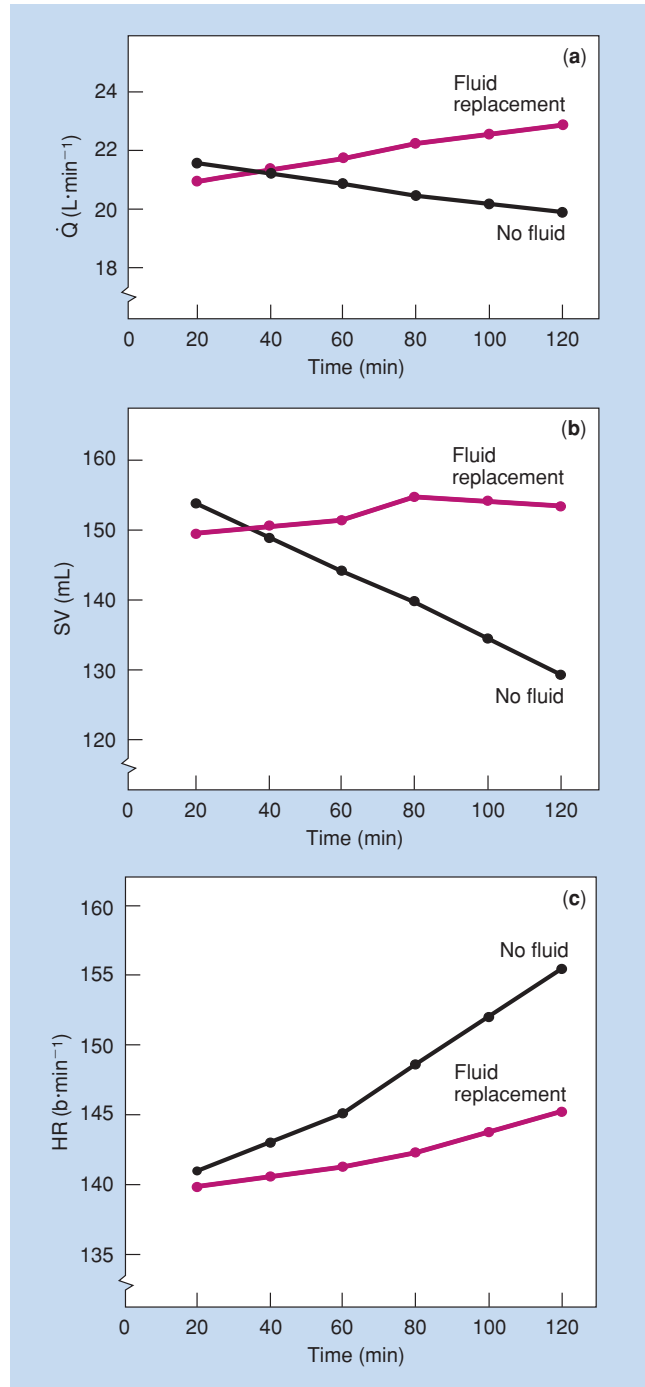

Figure 13.5

Cardiovascular Response to Long-Term, Moderate to Heavy Exercise (70–76% $\dot{V}O_2$max) with and without Fluid Replacement

Source: M. T. Hamilton, J. G. Alonso, S. J. Montain, & E. F. Coyle. Fluid replacement and glucose infusion during exercise prevents cardiovascular drift. *Journal of Applied Physiology.* 71:871–877 (1985). Reprinted by permission.

1991). Values are for minutes 20 through 120; thus, the initial increase in each of the variables is not shown in this figure. When subjects consumed enough water to completely replace the water lost through

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**Cardiovascular Drift** The changes in observed cardiovascular variables that occur during prolonged, heavy submaximal exercise without a change in workload.

Focus on Research

Interval Exercise versus Steady State Exercise

Foster, C., K. Meyer, N. Georgakopoulos, A. J. Ellestad, D. J. Fitzgerald, K. Tilman, H. Weinstein, H. Young, & H. Roskamm: Left ventricular function during interval and steady state exercise. *Medicine and Science in Sports and Exercise.* 31(8):1157–1162 (1999).

Throughout this book, we examine the exercise response to various categories of exercise, with this chapter looking specifically at the cardiovascular responses. Most studies that have examined the cardiovascular response to exercise have used continuous activity. Yet many clinical populations (for example, people undergoing cardiac rehabilitation) and many athletic populations utilize interval training. So how do these activities compare in terms of cardiovascular responses?

Foster and colleagues set out to answer this question by comparing the cardiovascular responses of a group of adults (mean age = 52.9 yr) in two separate 15-minute cycling trials—one involving steady state exercise, the other utilizing interval exercise. Participants cycled at 170 W for the full 15 minutes in one trial and alternated 1-min "hard" (220 W) and "easy" (120 W) periods in the second trial, resulting in an equal power output (170 W) for both trials. Cardiovascular measurements were obtained before exercise (0 minutes) and after minutes 4, 7, 12, and 15.

As can been seen from the results, no significant difference was noted between the steady state exercise and the interval exercise for any of the variables. The authors concluded that heart function during interval exercise is remarkably similar to
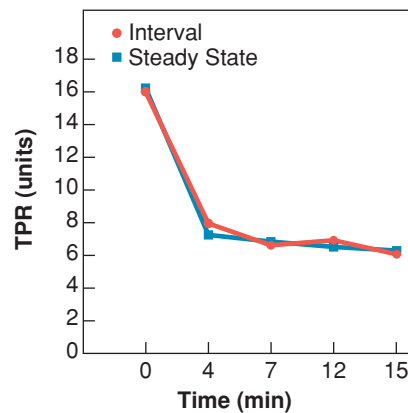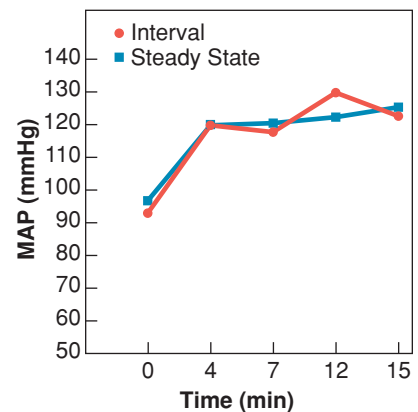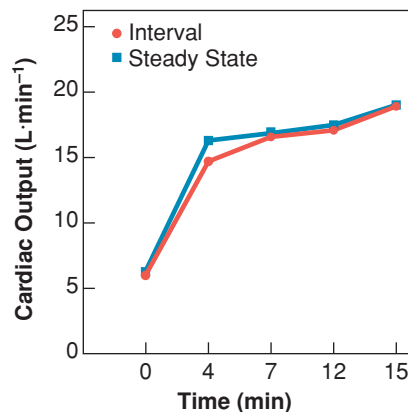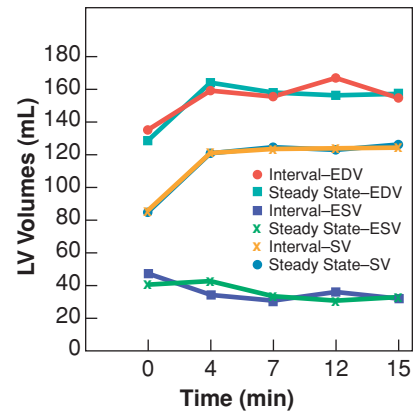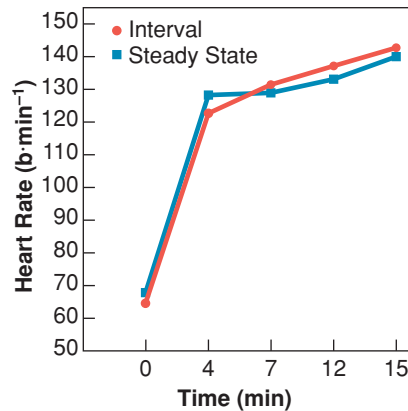
continuous steady state exercise at the same average power output, when moderate duration and evenly timed hard and easy periods are utilized. The results provide good news for individuals with low levels of fitness who may not be able to perform

15 minutes of continuous activity when starting an exercise program. Fitness professionals can assure such clients that alternating periods of "hard" and "easy" work results in cardiovascular responses similar to those resulting from sustained exercise.

sweat, cardiac output remained nearly constant throughout the first hour of exercise and actually increased during the second hour (Figure 13.5a). Cardiac output was maintained in the fluid replacement

trial because stroke volume did not drift downward (Figure 13.5b). Heart rate was significantly lower when fluid replacement occurred (Figure 13.5c). This information can be used by coaches and fitness
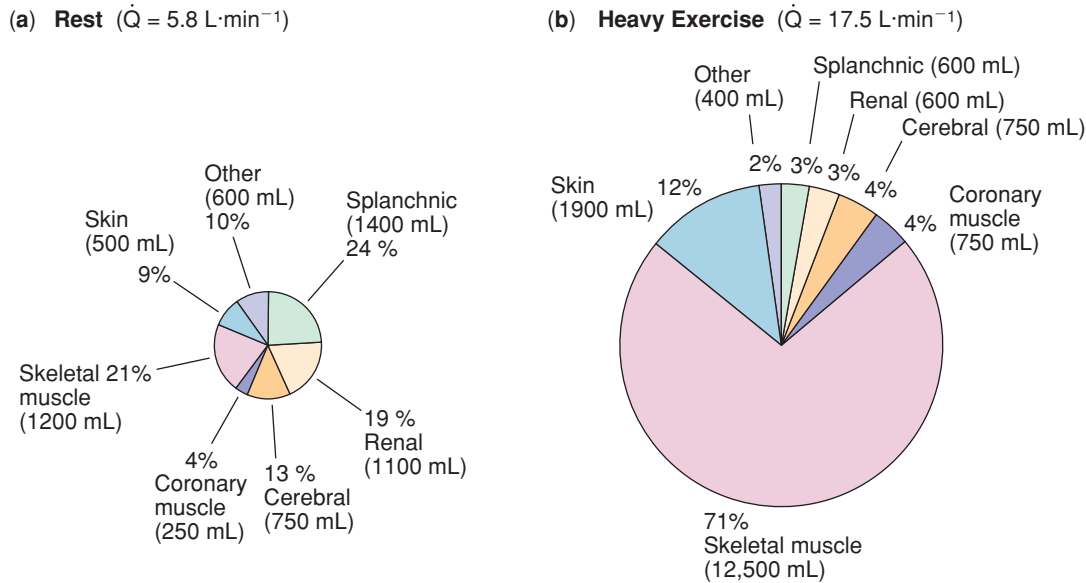
(a) **Rest** ($\dot{Q}$ = 5.8 L·min^{-1})

(b) **Heavy Exercise** ($\dot{Q}$ = 17.5 L·min^{-1})

Figure 13.6
Distribution of Cardiac Output at Rest and during Heavy Exercise

Source: Data from Anderson (1968).

leaders. If your clients exercise for prolonged periods, they must replace the fluids that are lost during exercise, or performance will suffer.

Refer back to the cardiovascular responses illustrated in Figure 13.4. Systolic blood pressure responses to long-term, moderate to heavy dynamic exercise are characterized by an initial increase, a plateau at steady state, and a negative drift. Systolic blood pressure increases rapidly during the first 1–2 min of exercise, with the magnitude of the increase dependent upon the intensity of the exercise (Figure 13.4d). Systolic blood pressure then remains relatively stable or drifts slightly downward as a result of continued vasodilation and a resultant decrease in resistance (Ekelund and Holmgren, 1967). Diastolic blood pressure does not change or changes so little that it has no physiological significance during prolonged exercise in a thermoneutral environment. But it may decrease slightly when exercise is performed in a warm environment owing to increased vasodilation as a result of heat production. Because of the increased systolic blood pressure and the relatively stable diastolic blood pressure, mean arterial pressure increases modestly during prolonged activity. Again, as in light to moderate exercise, the magnitude of the increase in mean arterial pressure is mediated by a large decrease in resistance that accompanies exercise.

Total peripheral resistance exhibits a curvilinear decrease during long-term heavy exercise (Figure 13.4e) because of vasodilation in active muscle and because of vasodilation in the cutaneous vessels in order to dissipate the heat produced by mechanical work (Rowell, 1974). Finally, because both heart rate and

systolic blood pressure increase substantially during heavy work, the rate-pressure product increases markedly (Figure 13.4f). The initial increase in rate-pressure product occurs rapidly with the onset of exercise and plateaus at steady state. An upward drift in rate-pressure product may occur after approximately 30 min of exercise as a result of heart rate increasing to a greater extent than systolic blood pressure decreases. The high rate-pressure product reflects the large amount of work the heart must perform to support heavy exercise.

During prolonged exercise, particularly if performed in the heat, there is continued loss of total body fluid owing to profuse sweating. Total body water loss during long-duration exercise varies from 900 to 1300 mL·hr^{-1}, depending on work intensity and environmental conditions (Wade and Freund, 1990). If fluid is not replaced during long-duration exercise, there is a continued reduction in plasma volume throughout exercise.

Figure 13.6 illustrates the distribution of cardiac output at rest and during heavy exercise. Notice that cardiac output increases from 5.8 L·min^{-1} at rest to 17.5 L·min^{-1} in this example. The most dramatic change in cardiac output distribution with heavy exercise is the dramatic increase in blood flow to the working muscle, which now receives 71% of cardiac output. Skin blood flow is also increased to meet the thermoregulatory demands of exercise. The absolute amount of blood flow to the coronary muscle again increases although the percentage of cardiac output remains relatively constant. The absolute amount of cerebral blood flow remains constant, which means that the
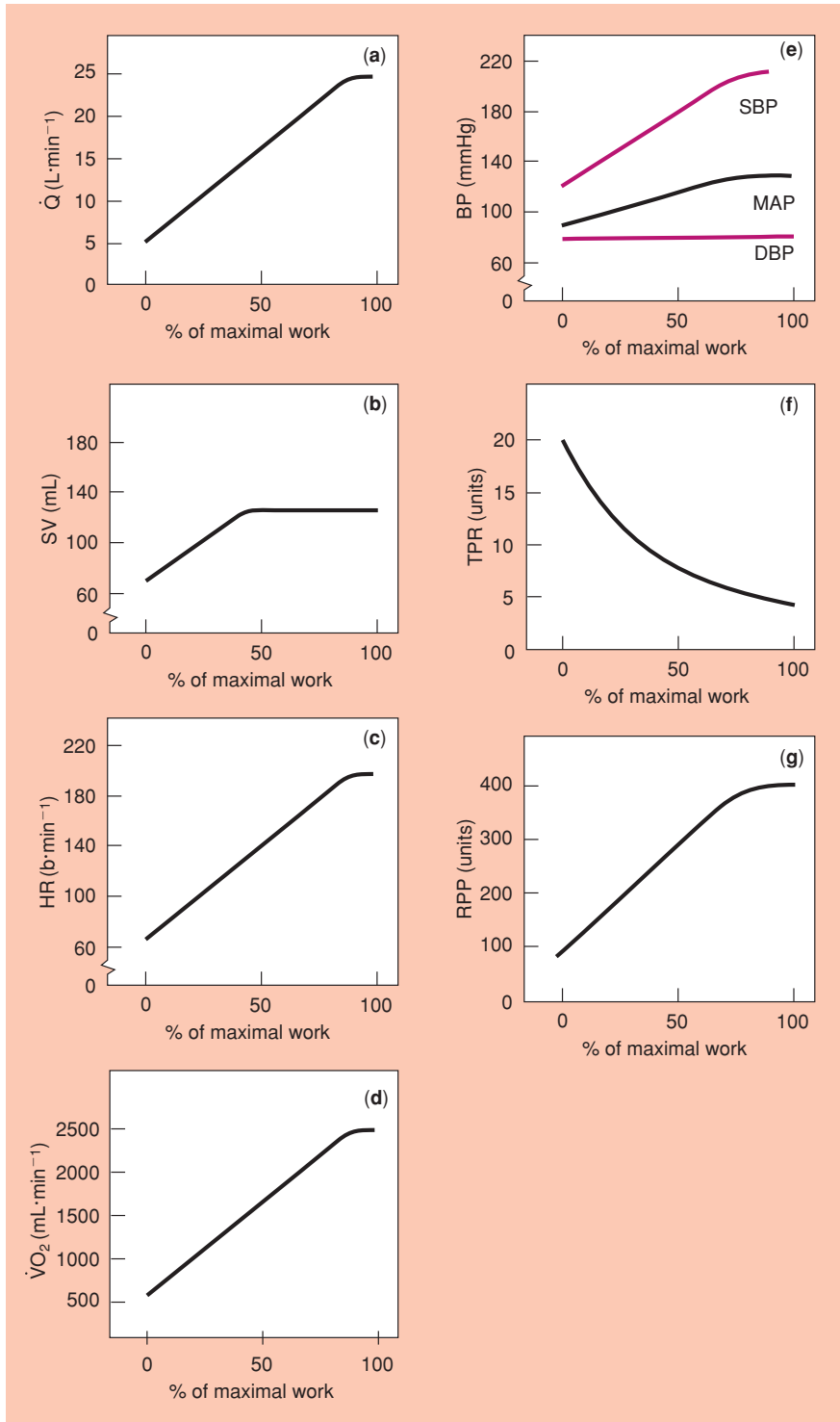
Figure 13.7
Cardiovascular Response to Incremental Maximal Exercise

percentage of cardiac output distributed to the neural tissue decreases. Both renal and splanchnic blood flow are further decreased as exercise intensity increases.

Incremental Aerobic Exercise to Maximum

An incremental exercise to maximum bout consists of a series of progressively increasing work intensities that continue until the individual can do no more. The length of each work intensity (stage) varies from 1 to 3 min to allow for the achievement of a steady state, at least at the lower workloads.

Cardiac output displays a rectilinear increase and plateaus at maximal exercise (Figure 13.7a). The initial increase in cardiac output reflects an increase in stroke volume and heart rate; however, at workloads
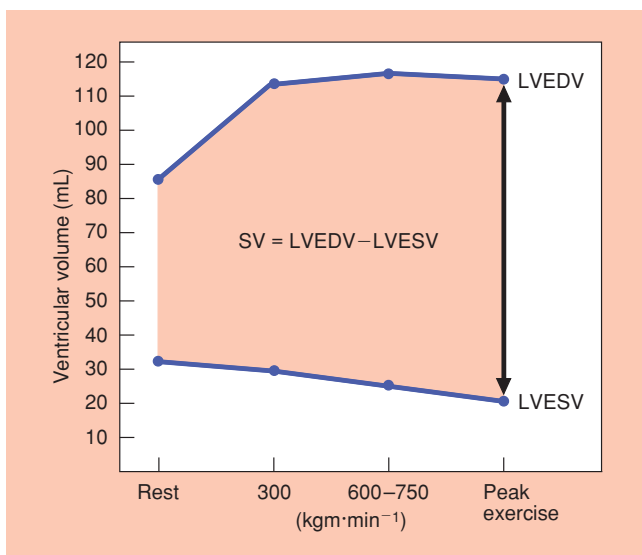
Figure 13.8

Changes in LVEDV and LVESV That Account for Change in SV during Incremental Exercise

Source: Based on data from Poliner, et al. (1980).

greater than 40–50% $\dot{V}O_2$max, the increase in cardiac output is achieved solely by an increase in heart rate. As shown in Figure 13.7b, in normally active individuals stroke volume increases rectilinearly initially and then plateaus at approximately 40–50% of $\dot{V}O_2$max (P. Åstrand, et al., 1964; Higginbotham, et al., 1986). Stroke volume may actually decrease slightly near the end of maximal exercise in untrained and moderately trained individuals (Gledhill, et al., 1994).

Figure 13.8 indicates the changes in left ventricular end–diastolic volume and left ventricular end–systolic volume that account for changes in stroke volume during progressively increasing exercise (Poliner, et al., 1980). Left ventricular end–diastolic volume increases largely because of the return of blood to the heart by the active muscle pump and the increased sympathetic outflow to the veins causing venoconstriction and augmenting venous return. Left ventricular end–systolic volume decreases because of augmented contractility of the heart, which ejects more blood from the ventricle and leaves less in the ventricle.

Heart rate increases in a rectilinear fashion and plateaus at maximal exercise (Figure 13.7c). The myocardial cells are capable of contracting at over 300 b·min^{-1} but rarely exceeds 210 b·min^{-1} because a faster heart rate would not be of any benefit since there would be inadequate time for ventricular filling. Thus, stroke volume and ultimately cardiac output would be decreased. Consider the simple analogy of a bucket brigade. Up to a certain point it is very useful to increase the speed of passing the bucket; however,

there is a limit to this speed because some time must be allowed for the bucket to be filled with water.

The maximal amount of oxygen an individual can take in, transport, and utilize ($\dot{V}O_2$max) is another variable that is usually measured during an incremental maximal exercise test (Figure 13.7d). Although $\dot{V}O_2$max is considered primarily a cardiovascular variable, it also depends on the respiratory and metabolic systems. As noted in Chapter 12, $\dot{V}O_2$max can be defined by rearranging the Fick equation (Eq. 12.9) to the following equation, as described in Equation 12.14b.

13.1 $\dot{V}O_2\text{max} = (\dot{Q}\text{ max}) \times (\text{a-v}O_2 \text{ diff max})$

The changes in cardiac output during a maximal incremental exercise test have just been described (a rectilinear increase). The changes in the a-vO_2 diff were discussed in Chapter 11 (an increase plateauing at approximately 60% of $\dot{V}O_2$max). Reflecting these changes, oxygen consumption ($\dot{V}O_2$) also increases in a rectilinear fashion and plateaus at maximum ($\dot{V}O_2$max) during an incremental exercise test to maximum. The plateauing of $\dot{V}O_2$ is one of the primary indications that a true maximal test has been achieved.

The arterial blood pressure responses to incremental dynamic exercise to maximum are shown in Figure 13.7e. Systolic blood pressure increases rectilinearly and plateaus at maximal exercise, often reaching values in excess of 200 mmHg in very fit individuals. The increase in systolic blood pressure is caused by the increased cardiac output, which outweighs the decrease in resistance. Systolic blood pressure and heart rate are two variables that are routinely monitored during an exercise test to ensure the safety of the participant. If either of these variables fails to rise with an increasing workload, cardiovascular insufficiency and an inability to adequately profuse tissue may result, and the exercise test should be stopped.

Diastolic blood pressure typically remains relatively constant or changes so little it has no physiological significance, although it may decrease at high levels of exercise. Diastolic pressure remains relatively constant because of the balance of vasodilation in the vasculature of the active muscle and vasoconstriction in other vascular beds. Diastolic pressure is most likely to decrease when exercise is performed in a hot environment; under these conditions skin vessels are more dilated, and there is decreased resistance to blood flow.

An excessive rise in either systolic blood pressure (over 260 mmHg) or diastolic blood pressure (over 115 mmHg) indicates an abnormal exercise response and is also reason to consider stopping an exercise test or exercise session (American College of Sports Medicine [ACSM], 2000). Individuals who exhibit an exaggerated blood pressure response to exercise are
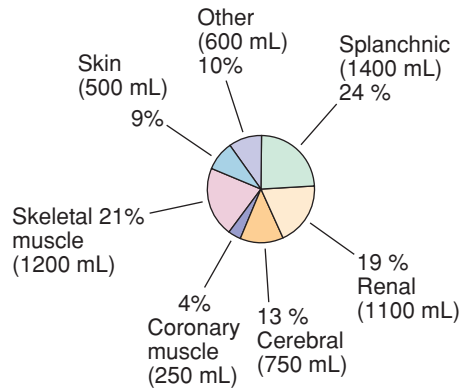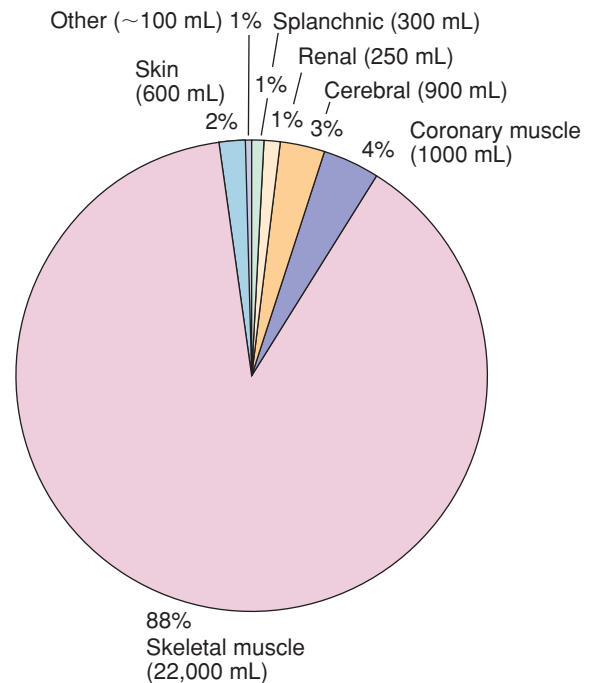
(a) Rest ($\dot{Q}$ = 5.8 L·min^{-1})

(b) Maximal Exercise ($\dot{Q}$ = 25 L·min^{-1})

Other (~100 mL) 1% Splanchnic (300 mL)

Skin (600 mL) 1% Renal (250 mL)

Cerebral (900 mL)

2% 1% 3%

Coronary muscle
4% (1000 mL)

Other (600 mL) 10%

Splanchnic (1400 mL) 24 %

Skin (500 mL) 9%

Skeletal 21% muscle (1200 mL)

19 % Renal (1100 mL)

4% Coronary muscle (250 mL)

13 % Cerebral (750 mL)

88% Skeletal muscle (22,000 mL)

Figure 13.9
Distribution of Cardiac Output at Rest and during Maximal Exercise

Source: Data from Anderson (1968).

two to three times more likely to develop hypertension than those with a normal exercise blood pressure response (ACSM, 1993).

Total peripheral resistance decreases in a negative curvilinear pattern and reaches its lowest level at maximal exercise (Figure 13.7f). Decreased resistance reflects maximal vasodilation in the active tissue in response to the need for increased blood flow that accompanies maximal exercise. Also, the large drop in resistance is important in keeping mean arterial pressure from exhibiting an exaggerated increase. The rate-pressure product increases in a rectilinear fashion plateauing at maximum in an incremental exercise test (Figure 13.7g), paralleling the increases in heart rate and systolic blood pressure.

The reduction in plasma volume seen during submaximal exercise is also seen in incremental exercise to maximum. Because the magnitude of the reduction depends on the intensity of exercise, the reduction is greatest at maximal exercise. A decrease of 10–20% can be seen during incremental exercise to maximum (Wade and Freund, 1990).

Considerable changes in blood flow occur during maximal incremental exercise. Figure 13.9 illustrates the distribution of cardiac output at rest and at maximal exercise. Maximum cardiac output in this

example is 25 L·min^{-1}. Again, the most striking characteristic of this figure is the tremendous amount of cardiac output that is directed to the working muscles (88%). At maximal exercise skin blood flow is reduced in order to direct the necessary blood to the muscles. Renal and splanchnic blood flow also decrease considerably. Blood flow to the brain and cardiac muscle is maintained.

Table 13.1 summarizes the cardiovascular responses to exercise that have been discussed in these sections.

Upper-Body versus Lower-Body Aerobic Exercise

Upper-body exercise is routinely performed in a variety of industrial, agricultural, military, and sporting activities. There are some important differences in the cardiovascular responses, depending on whether exercise is performed on an arm ergometer (using muscles of the upper body) or a cycle ergometer (using muscles of the lower body). Figure 13.10 presents data from a study that compared cardiovascular responses to incremental exercise to maximum in able-bodied individuals using the upper body and lower body. Notice that a higher peak $\dot{V}O_2$ was achieved during lower-body

Table 13.1
Cardiovascular Responses to Exercise*

	Short-Term, Light to Moderate Submaximal Aerobic Exercise	Long-Term, Moderate to Heavy Submaximal Aerobic Exercise[†]	Incremental Aerobic Exercise to Maximum	Static[††] Exercise	Resistance[††] Exercise
$\dot{Q}$	Increases rapidly; plateaus at steady state within 2 min	Increases rapidly; plateaus	Rectilinear increase with plateau at max	Modest gradual increase	Modest gradual increase
SV	Increases rapidly; plateaus at steady state within 2 min	Increases rapidly; plateaus; negative drift	Increases initially; plateaus at 40–50% $\dot{V}O_2$max	Relatively constant at low workloads; decreases at high workloads; rebound rise in recovery	Little change, slight decrease
HR	Increases rapidly; plateaus at steady state within 2 min	Increases rapidly; plateaus; positive drift	Rectilinear increase with plateau at max	Modest gradual increase	Increases gradually with numbers of reps
SBP	Increases rapidly; plateaus at steady state within 2 min	Increases rapidly; plateaus; slight negative drift	Rectilinear increase with plateau at max	Marked steady increase	Increases gradually with numbers of reps
DBP	Shows little or no change	Shows little or no change	Shows little or no change	Marked steady increase	No change or increase
MAP	Increases rapidly; plateaus at steady state within 2 min	Increases initially; little if any drift	Small rectilinear increase	Marked steady increase	Increases gradually with numbers of reps
TPR	Decreases rapidly; plateaus	Decreases rapidly; plateaus; slight negative drift	Curvilinear decrease	Decreases	Slight increase
RPP	Increases rapidly; plateaus at steady state within 2 min	Increases rapidly; plateaus; positive drift	Rectilinear increase with plateau at max	Marked steady increase	Increases gradually with numbers of reps

*   Resting values are taken as baseline.

†   The difference between a plateau during the short-term, light to moderate and long-term, moderate to heavy submaximal exercise response is one of magnitude; that is, a plateau occurs at a higher value with higher intensities.

††   The magnitude of a plateau change depends on the %MVC/load.

exercise. By comparing cardiovascular responses at any given level of oxygen consumption, these data also allow for the comparison of cardiovascular responses to submaximal upper- and lower-body exercise. When the oxygen consumption required to perform a submaximal workload is the same, cardiac output is similar for upper- and lower-body exercise (Figure 13.10a). However, the mechanism to achieve the required increase in cardiac output is not the same. As shown in Figures 13.10b and 13.10c, upper-body exercise results in a lower stroke volume and a higher heart rate at any given submaximal workload (Clausen, 1976; Miles, et al., 1989; Pendergast, 1989). Systolic, diastolic, and mean arterial blood pressures (Figure 13.10d), total peripheral resistance (Figure 13.10e), and rate-pressure product (Figure 13.10f) are significantly higher in upper-body exercise than in lower-body exercise performed at the same oxygen consumption.

There are several likely reasons for the differences in cardiovascular responses to upper-body and lower-body exercise. The elevated heart rate is thought to reflect a greater sympathetic stimulation during upper-body exercise (P. O. Åstrand and Rodahl, 1986; Davies, et al., 1974; Miles, et al., 1989). Stroke volume is less during upper-body exercise than during lower-body exercise because of the absence of the skeletal muscle pump augmenting venous return from the legs. The greater sympathetic stimulation that occurs during upper-body exercise may also be partially responsible for the increased blood pressure and total peripheral resistance seen with this type of activity. Additionally, upper-body exercise is usually performed using an arm-cranking ergometer, which involves a static component because the individual must grasp the hand crank. Static tasks are known to cause exaggerated blood pressure responses.
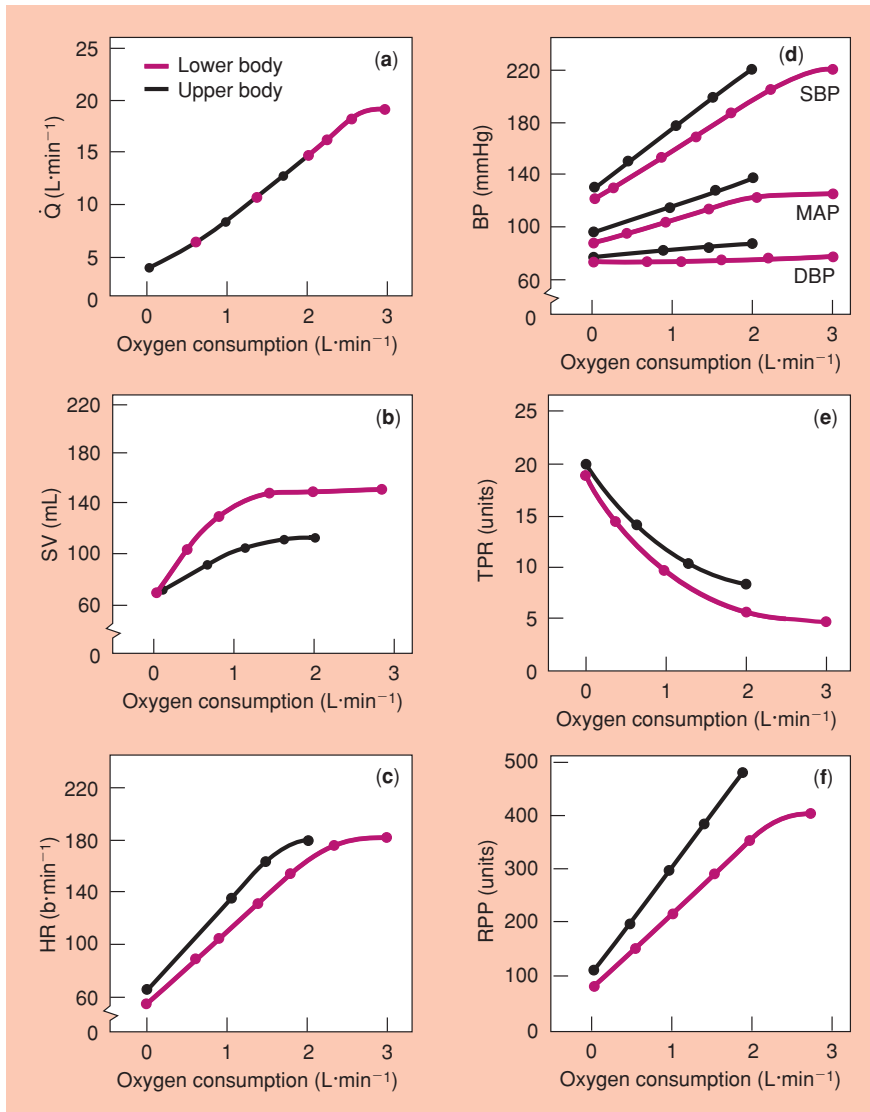
Figure 13.10
Cardiovascular Response to Incremental Maximal Upper-Body and Lower-Body Exercise

When maximal exercise is performed by using upper-body exercise, $\dot{V}O_2$max values are approximately 30% lower than when maximal exercise is performed by using lower-body exercise (Miles, et al., 1989; Pendergast, 1989). Maximal heart rate values for upper-body exercise are 90–95% of those achieved for lower-body exercise, and stroke volume is 30–40% less during maximal upper-body exercise. Maximal systolic blood pressure and the rate-pressure product are usually similar for both forms of exercise, but diastolic blood pressure is typically 10–15% higher during upper-body exercise (Miles, et al., 1989).

The different cardiovascular responses to a given level of exercise for upper-body work and lower-body work suggest that exercise prescriptions for arm work cannot be based on data obtained from testing with leg exercises. Furthermore, the greater cardiovascular strain associated with upper-body work must be kept in mind when one prescribes exercise for individuals with cardiovascular disease.

Sex Differences during Aerobic Exercise

The pattern of cardiovascular responses to aerobic exercise is similar for both sexes, although the magnitude of the response may vary between the sexes for some variables. Differences in body size and structure are related to many of the differences in cardiovascular responses evidenced between the sexes.

Submaximal Exercise

Females have a higher cardiac output than males during submaximal exercise when work is performed at the same *absolute workload* (P. Åstrand, et al., 1964; Becklake, et al., 1965; Freedson, et al., 1979).
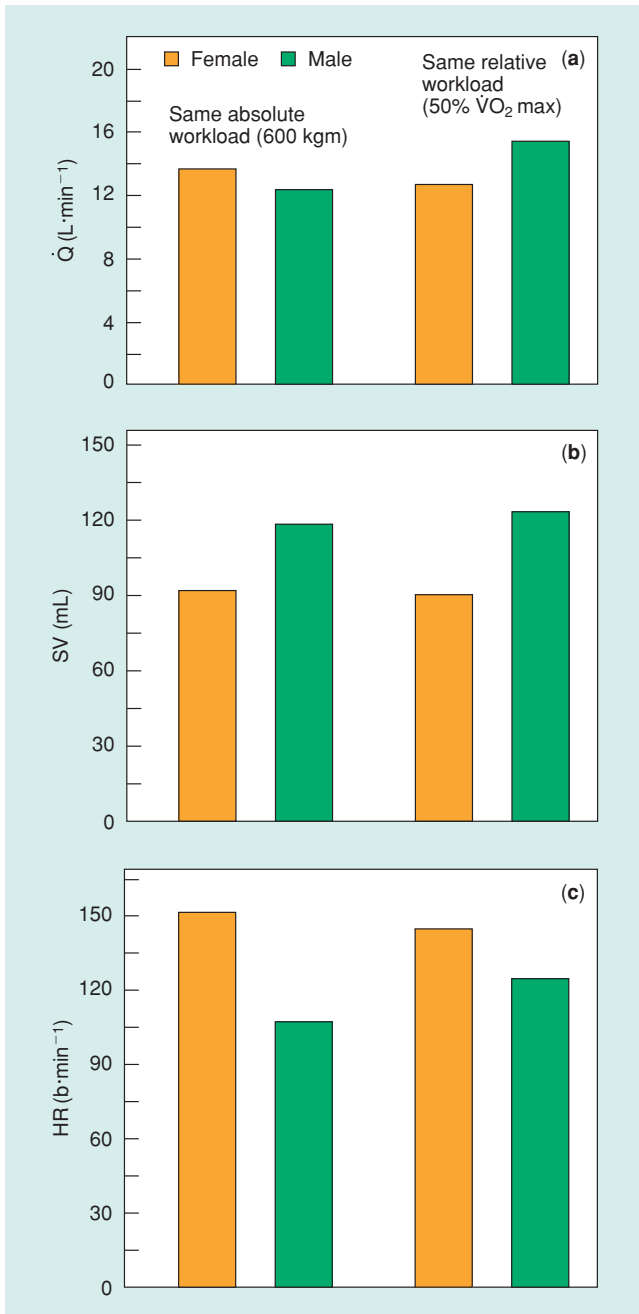
Figure 13.11

Comparison of Cardiovascular Responses of Men and Women to Submaximal Exercise

Source: Data from P. Åstrand (1952).

Females have a lower stroke volume and a higher heart rate than males during submaximal exercise when exercise is performed at the same absolute workload (P. Åstrand, et al., 1964). The higher heart rate more than compensates for the lower stroke volume in females, resulting in the higher cardiac output seen at the same absolute workload. Thus, if a male

and female perform the same workout, the female will typically be stressing the cardiovascular system to a greater extent.

This relative disadvantage to the woman results from several factors. First, females typically are smaller than males; they have a smaller heart and less muscle mass. Second, they have a lower oxygen-carrying capacity than males. Finally, they typically have lower aerobic capacity ($\dot{V}O_2$max). Therefore, researchers commonly discuss exercise response in terms of *relative workload,* that is, how individuals compare when they are both working at the same percentage of their $\dot{V}O_2$max.

The importance of distinguishing between relative and absolute workloads when comparing males and females is shown in Figure 13.11. This figure compares the cardiovascular response of men and women to the same absolute workload (600 kgm) on the left side of the graph and the same relative workload (50% of $\dot{V}O_2$max) on the right side of the graph. Cardiac output is higher in women during the same absolute workload. However, cardiac output (Figure 13.11a) is less for women when the same relative workload is performed. Stroke volume (Figure 13.11b) is lower in women than in men whether the workload is expressed on an absolute or relative basis. Notice that the values are very similar for both conditions, suggesting that stroke volume has plateaued as would be expected at 50% of $\dot{V}O_2$max in both conditions. The difference in heart rate between the sexes (Figure 13.11c) is smaller when exercise is performed at the same relative workload.

Males and females display the same pattern of response for blood pressure; however, males tend to have a higher systolic blood pressure than females at the same relative workloads (Malina and Bouchard, 1991; Ogawa, et al., 1992). Much of the difference in the magnitude of the blood pressure response is attributable to differences in resting systolic blood pressure. Diastolic blood pressure response to submaximal exercise is very similar for both sexes. Thus, mean arterial blood pressure is slightly greater in males during submaximal work at the same relative workload. The pattern of response for resistance is similar for males and females, although males typically have a lower resistance owing to their greater cardiac output. Males and females both exhibit cardiovascular drift during heavy, prolonged submaximal exercise.

Incremental Exercise to Maximum

The cardiovascular response to incremental exercise is similar for both sexes, although, again, there are differences in the maximal values attained. Maximal oxygen consumption ($\dot{V}O_2$max) is higher for males
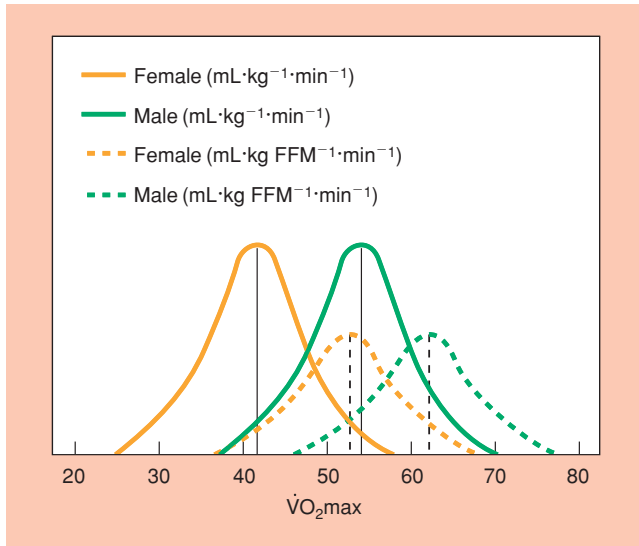
Figure 13.12
Distribution of $\dot{V}O_2$max for Males and Females

Source: C. L. Wells & S. A. Plowman. Sexual differences in athletic performance: Biological or behavioral? *Physician and Sports Medicine.* 11(8): 52–63 (1983). Reprinted by permission.

than for females. When $\dot{V}O_2$max is expressed in absolute values (liters per minute), males typically have values that are 40–60% higher than in females (P. Åstrand, 1952; Sparling, 1980). When differences in body size are considered and $\dot{V}O_2$max values are reported on the relative basis of body weight (in milliliters per kilogram per minute), the differences between the sexes decreases to 20–30%. If differences in body composition are considered and $\dot{V}O_2$max is expressed relative to fat-free mass (in milliliters per kilogram of fat-free mass per minute), the difference between the sexes is reduced to 0–15% (Sparling, 1980). Reporting $\dot{V}O_2$max relative to fat-free mass is important in terms of understanding the influence of adiposity and fat-free mass in determining $\dot{V}O_2$max. However, it is not a very practical way to express $\dot{V}O_2$max because, in reality, consuming oxygen in relation to only the fat-free mass is not an option. Individuals cannot leave their fat mass behind when exercising.

Figure 13.12 represents the distribution of $\dot{V}O_2$max values for males and females expressed per kilogram of weight and per kilogram of fat-free mass. This figure demonstrates the important point that there is considerable variability in $\dot{V}O_2$max for both sexes. Thus, although males generally have a higher $\dot{V}O_2$max than females, some females will have a higher $\dot{V}O_2$max than the average man.

Figure 13.13 shows the differences in $\dot{V}O_2$max, expressed in relative terms (Figure 13.13a) and absolute terms (Figure 13.13b) and body weight (Figure
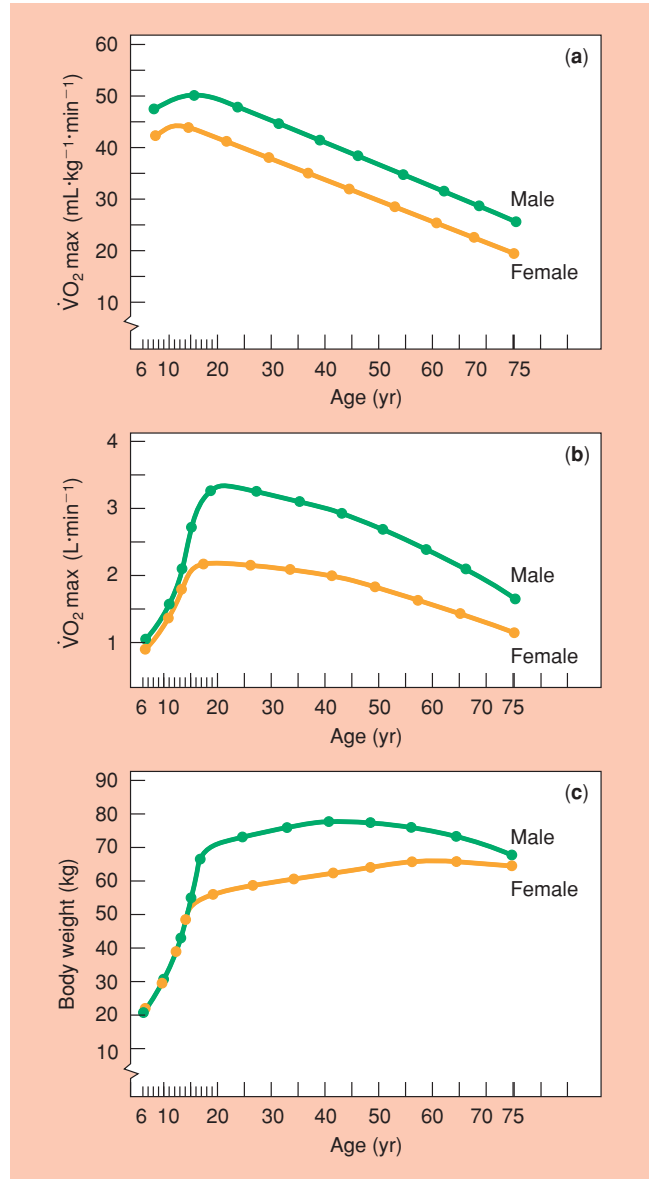
Figure 13.13
Maximal Oxygen Consumption ($\dot{V}O_2$max) and Weight for Males and Females from 6–75 Years

Source: E. Shvartz & R. C. Reibold. Aerobic fitness norms for males and females aged 6 to 75 years: A review. *Aviation, Space, and Environmental Physiology.* 61:3–11 (1990). Reprinted by permission.

13.13c) between the sexes across the age span. Differences in $\dot{V}O_2$max between the sexes is largely explained by differences in the size of the heart (and thus maximal cardiac output) and differences in the oxygen-carrying capacity of the blood. Males have approximately 6% more red blood cells and 10–15% more hemoglobin than females; thus, males have a greater oxygen-carrying capacity than females (P. Åstrand and Rodahl, 1986).

Table 13.2

Cardiovascular Variables for Women When Compared to Men

Variable	Rest	Exercise Condition		
		Absolute, Submaximal	**Relative, Submaximal**	**Incremental, Maximal**
$\dot{V}O_2$max	—	—	—	Lower
$\dot{Q}$	Lower	Higher	?	Lower
SV	Lower	Lower	Lower	Lower
HR	Higher	Higher	Higher	Similar

Source: Wells (1991).

Males typically have maximal cardiac output values that are 30% higher than those of females (Wells, 1985). Maximal stroke volume is higher for men, but the increase in stroke volume during maximal exercise is achieved by the same mechanisms in both sexes (Sullivan, et al., 1991). Furthermore, if maximal stroke volume is expressed relative to body weight, there is no difference between the sexes. The maximal heart rate is similar for both sexes.

Males and females display the same pattern of blood pressure response; however, males attain a higher systolic blood pressure than females at maximal exercise (Malina and Bouchard, 1991; Ogawa, et al., 1992; Wanne and Haapoja, 1988). Diastolic blood pressure response to maximal exercise is similar for both sexes. Thus, mean arterial blood pressure is slightly greater in males at the completion of maximal work. The pattern of response for resistance and rate-pressure product is the same for both sexes. Resistance is greatly reduced during maximal exercise in both sexes. Because the heart rate response is similar and because systolic blood pressure is greater in males, males tend to have a higher rate-pressure product at maximal exercise levels than do females.

Table 13.2 summarizes the differences between the sexes in cardiovascular variables at various exercise levels.

Responses of Children to Aerobic Exercise

The responses of children to cardiovascular exercise are similar to the responses of adults. However, there are differences in the magnitude of the responses primarily because of differences in body size and structure.

Submaximal Exercise

The pattern of cardiac output response to submaximal dynamic exercise is similar in children and adults, with cardiac output increasing rapidly at the onset of exercise and plateauing when steady state is achieved. However, children have a lower cardiac output than adults at all levels of exercise, primarily because children have a lower stroke volume than adults at any given level of exercise (Bar-Or, 1983; Rowland, 1990). The lower stroke volume in children is compensated for, to some extent, by a higher heart rate. Stroke volume in girls is less than that in boys at all levels of exercise (Bar-Or, 1983).

The magnitude of the cardiovascular response depends on the intensity of the exercise. Table 13.3 reports the cardiac output, stroke volume, and heart rate values of children 8–12 years old during treadmill exercise at 40%, 53%, and 68% of $\dot{V}O_2$max (Lussier and Buskirk, 1977). Both cardiac output and heart rate increase in response to increasing intensities of exercise. Stroke volume peaks at 40% of $\dot{V}O_2$max and changes little with increasing exercise intensity. This is consistent with the finding that stroke volume plateaus at 40–50% of $\dot{V}O_2$max in adults (P. Åstrand, et al., 1964).

Although the pattern of response in children is similar to that of adults, a careful review of Table 13.3 reveals that the values for cardiac output and stroke volume are much smaller in children. As children grow and mature, cardiac output and stroke volume increase at rest and during exercise. The heart rate response, by contrast, is higher in the younger children (Bar-Or, 1983; Cunningham et al., 1984).

Systolic blood pressure in children increases during exercise, as it does in adults, and depends on the intensity of the exercise. Boys tend to have a higher systolic blood pressure than girls (Malina and Bouchard, 1991). The magnitude of the increase in systolic pressure at submaximal exercise is less in children than in adults (James, et al., 1980; Wanne and Haapoja, 1988). The failure of systolic blood pressure to reach adult levels is probably the result of lower cardiac output in children. As children mature, the increases in systolic blood pressure during

Table 13.3

Cardiovascular Responses in Children to Submaximal
Exercise of Various Intensities

Variable	Intensity of Exercise (% $\dot{V}O_2$max)		
	40%	**53%**	**68%**
$\dot{Q}$ (L·min^{-1})	6.7	7.6	8.5
SV (mL·b^{-1})	53	51	49
HR (b·min^{-1})	126	149	173

Source: Lussier & Buskirk (1977).

exercise become greater. Diastolic pressure changes little during exercise but is lower in children than adults (James, et al., 1980; Wanne and Haapoja, 1988).

Similar decreases in resistance occur in children as in adults, owing to vasodilation in working muscles. Myocardial oxygen consumption and, thus, rate-pressure product increase in children during exercise. However, the work of the heart reflects the higher heart rate and lower systolic blood pressure for children than for adults. Blood flow through the exercising muscle appears to be greater in children than in adults, resulting in a higher a-vO_2 diff and thereby compensating partially for the lower cardiac output (Rowland, 1990; Rowland and Green, 1988). Children appear to exhibit cardiovascular drift during heavy, prolonged exercise, just as adults do (Asano and Hirakoba, 1984).

Incremental Exercise to Maximum

The cardiovascular responses to incremental exercise to maximum are similar for children and adults; however, children achieve a lower maximal cardiac output and a lower maximal stroke volume. Maximal heart rate is higher in children than in adults and is not age dependent until the late teens (Cunningham, et al., 1984; Rowland, 1996).

The maximal oxygen consumption that is typically attained by children between the ages of 6 and 18 is shown in Figure 13.14. As children grow, their ability to take in, transport, and utilize oxygen improves. This improvement represents dimensional and maturational changes—specifically, heart volume, maximal stroke volume, maximal cardiac output, blood volume and hemoglobin concentration, and a-vO_2 diff increase.

The rate of improvement in absolute $\dot{V}O_2$max (expressed in liters per minute) is similar for boys and girls until approximately 12 yr of age (Figure 13.14a). Maximal oxygen uptake continues to increase in boys until the age of 18; it remains relatively constant in girls between the ages of 14 and 18.
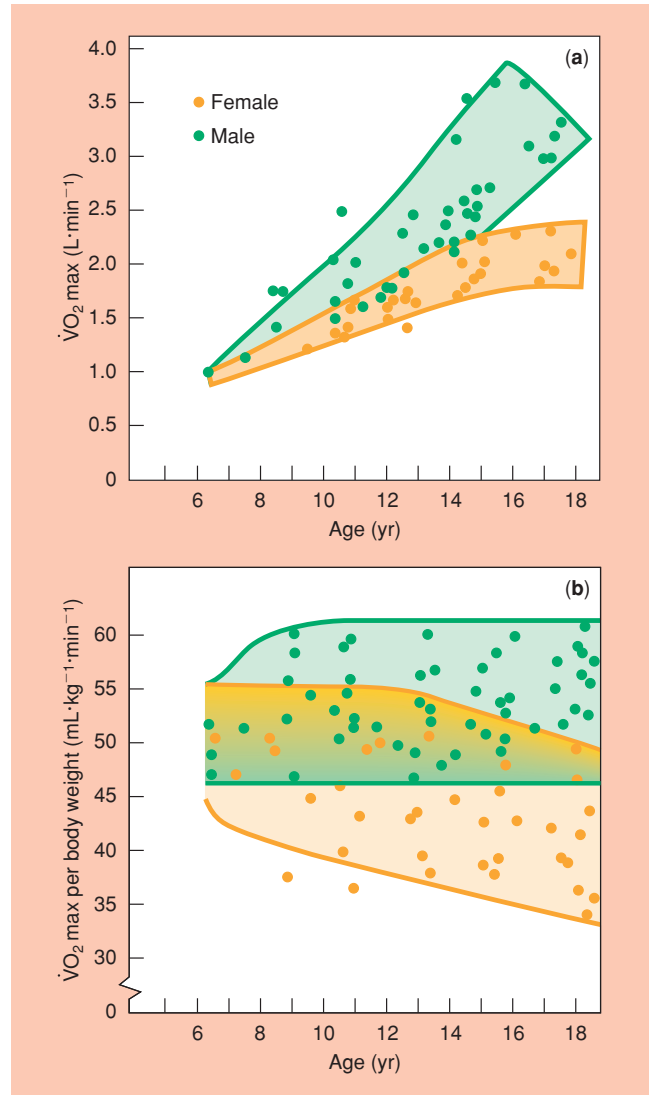

Figure 13.14
Maximal Oxygen Consumption
($\dot{V}O_2$max) of Children

(a) Changes in $\dot{V}O_2$max in children and adolescents during the ages of 6–18 are expressed in absolute terms. The dots represent means from various studies. The outer lines indicate normal variability in values. (b) Changes in $\dot{V}O_2$max in children and adolescents during the ages of 6–18 are expressed relative to body weight. The dots represent means from various studies. The outer lines indicate normal variability in reported values.

Source: O. Bar-Or. Physiologic principles to clinical applications. *Pediatric Sports Medicine for the Practitioner.* New York: Springer-Verlag (1983). Reprinted by permission.

When $\dot{V}O_2$max is expressed relative to body weight (expressed in milliliters per kilogram of body weight per minute), it remains relatively constant throughout the years between 8 and 16 for boys (Figure 13.14b). However, there is a tendency for the $\dot{V}O_2$max expressed per kilogram of body weight per

minute to decrease in girls as they enter puberty, and their adiposity increases (Figure 13.14b). As children mature, they also grow; and the developmental changes indicated previously are largely offset if $\dot{V}O_2$max is described per kilogram of body weight. Notice that in both parts of Figure 13.14 there is a large area of overlap for reported values of $\dot{V}O_2$max for boys and girls. This reflects the large variability in $\dot{V}O_2$max among children.

One major difference between children/adolescents and adults is the meaning of $\dot{V}O_2$max. In adults $\dot{V}O_2$max reflects both physiological function (cardiorespiratory power) and cardiovascular endurance (the ability to perform strenuous, large-muscle exercise for a prolonged period of time) (Taylor, et al., 1955). In children, $\dot{V}O_2$max is not as directly related to cardiorespiratory endurance as it is in adults (Bar-Or, 1983; Krahenbuhl, et al., 1985; Rowland, 1990). Figure 13.15b shows performance as determined by the number of stages or minutes completed in the PACER test (Léger, et al., 1988). This progressive, aerobic cardiovascular endurance run (PACER) was fully described in Chapter 12. Recall that a higher number of laps completed is positively associated with a higher $\dot{V}O_2$ max. Figure 13.15a shows that for boys the mean value of $\dot{V}O_2$max, expressed in $mL \cdot kg^{-1} \cdot min^{-1}$, changes very little from age 6 to 18 yr. However, mean performance on the PACER test (Figure 13.15b) shows a definite linear improvement with age. The girls show the same trend as the boys prior to puberty; but thereafter, $\dot{V}O_2$max declines steadily and PACER performance plateaus. Similar results are seen in treadmill endurance times and other distance runs (Cumming, et al., 1978). Thus, in general, endurance performance improves progressively throughout childhood, at least until puberty; but directly determined $\dot{V}O_2$max, expressed relative to body size, does not. Furthermore, at any given age the relationship between $\dot{V}O_2$max and endurance performance is weak.

The reason for the weak association between $\dot{V}O_2$max and endurance performance in young people is unknown. The most frequent suggestion is that children use more aerobic energy (require greater oxygen) at any submaximal pace than adults do. This phenomenon is called *running economy* and is fully discussed in the unit on metabolism. More important than the actual oxygen consumption at a set pace, however, may be the percentage of $\dot{V}O_2$max that value represents, and more so in children than adolescents (McCormack, et al., 1991). Other factors that may impact endurance running performance in children and adolescents include body composition, particularly the percentage body fat component; sprint speed, possibly as a reflection of a high percentage of muscle
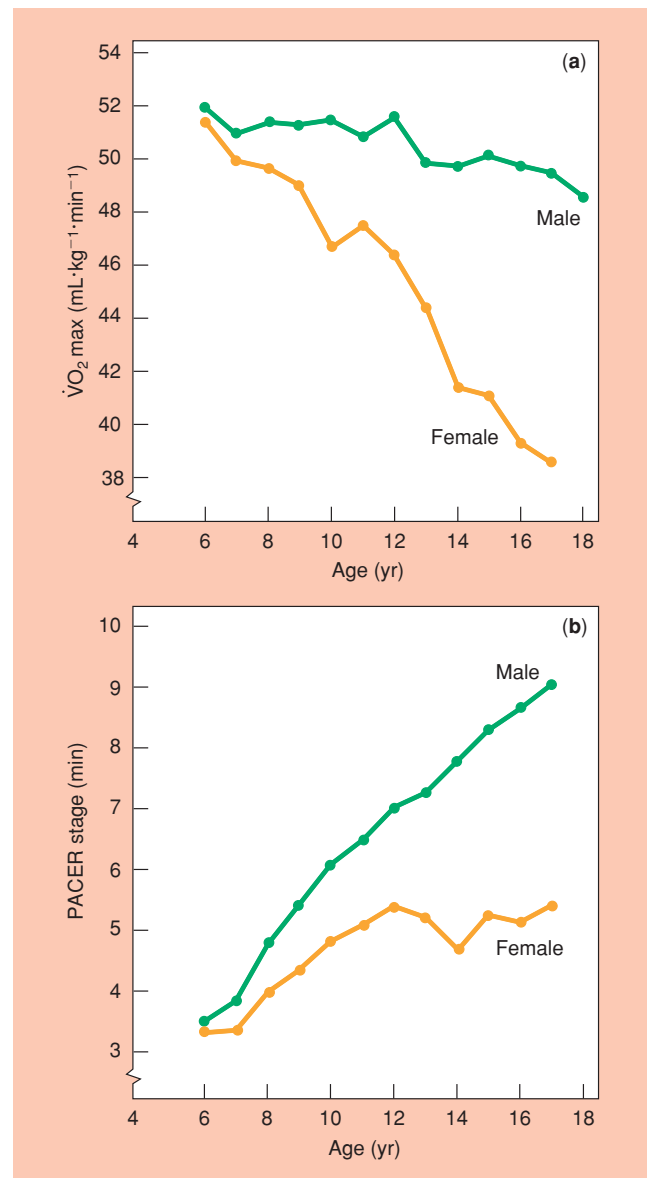
Figure 13.15

Maximal Oxygen Consumption ($\dot{V}O_2$max) and Endurance Performance in Children and Adolescents

Source: L. A. Léger, D. Mercer, C. Gadoury, & J. Lambert. The multistage 20 metre shuttle run test for aerobic fitness. *Journal of Sports Sciences.* 6:93–101 (1988). Modified and reprinted by permission.

fibers differentiated for speed and power; and various aspects of body size (Cureton, Baumgartner, et al., 1991; Cureton, Boileau, et al., 1977; Mayhew and Gifford, 1975; McVeigh, et al., 1995). There is also the possibility that many children and adolescents are not motivated to perform exercise tests and so do not perform well despite high $\dot{V}O_2$max capabilities.

Figure 13.16 presents the arterial blood pressure response of children and adolescents to incremental maximal exercise. The blood pressure response is

Figure 13.16

Blood Pressure Response of Children and Adolescents to an Incremental Exercise Test
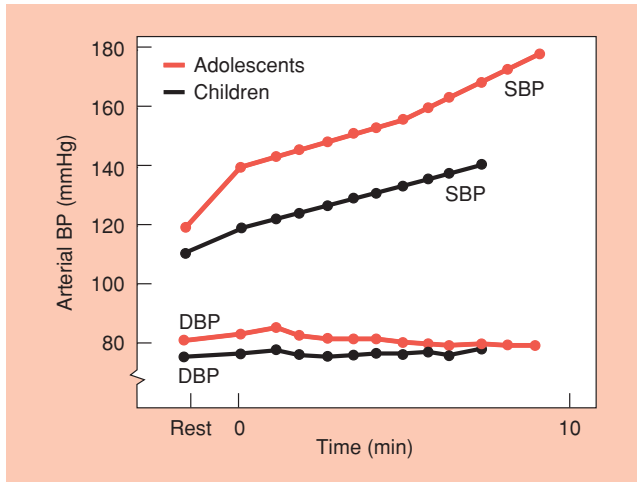
Source: D. A. Riopel, A. B. Taylor, & A. R. Hohn. Blood pressure, heart rate, pressure-rate product and electrocardiographic changes in healthy children during treadmill exercise. *American Journal of Cardiology.* 44(4): 697–704 (1979). Reprinted by permission.

similar for children and adults; however, there are again age- or size-related quantitative differences. For a given level of exercise, a small child responds with a lower systolic and diastolic blood pressure than does an adolescent, and an adolescent responds with lower blood pressure than an adult. The lower blood pressure response in young children is consistent with their lower stroke volume response. Typically, boys have a higher peak systolic blood pressure than girls (Riopel, et al., 1979; Wade and Freund, 1990). This difference too is most likely attributable to differences in stroke volume.

Table 13.4 reports typical cardiovascular responses to maximal exercise in pre- and postpubescent children.

Responses of the Elderly to Aerobic Exercise

Aging is associated with a loss of function in many systems of the body. Thus, aging is characterized by a decreased ability to respond to physiological stress (Skinner, 1993). There is considerable debate, though, about what portion of the loss of function that characterizes aging represents an inevitable age-related loss, what portion is related to disease, and what portion is attributable to the sedentary lifestyle that so often accompanies aging, because each causes similar decrements in function.

There are many examples of older adults who remain active into their later years and who perform amazing athletic feats. For example, Mavis Lindgren

Table 13.4

Cardiovascular Responses to Maximal Exercise in Pre- and Postpubescent Children

Variable	Boys 10 yr	Boys 15 yr	Girls 10 yr	Girls 15 yr
$\dot{Q}$ (L·min^{-1})	12	18	11	14
SV (mL·b^{-1})	60	90	55	70
HR (b·min^{-1})	200	200	200	200
$\dot{V}O_2$ (L·min^{-1})	1.7	3.5	1.5	2.0
SBP (mmHg)	144	174	140	170
DBP (mmHg)	64	64	64	64
MAP (mmHg)	105	110	103	117.5
TPR (units)	7.0	6.1	9.4	8.4
RPP (units)	290	350	280	340

Source: P. Åstrand (1952); Rowland (1990).

began an exercise program of walking when she was in her early sixties. She slowly increased her training volume and began jogging. At the age of 70 she completed her first marathon. In the next 12 years she raced in over fifty marathons (Nieman, 1990). Many studies of physical activity suggest that by remaining active in the older years, individuals can markedly reduce loss of cardiovascular function, even if they don't run a marathon.

Submaximal Exercise

At the same absolute submaximal workload, cardiac output and stroke volume are lower in older adults, but heart rate is higher when compared with those variables for younger adults. The pattern of systolic and diastolic pressure is the same for younger and older individuals. The difference in resting blood pressure is maintained throughout exercise, so that older individuals have a higher systolic, diastolic, and mean blood pressure at any given level of exercise (Ogawa, et al., 1992). The higher blood pressure response is related to a higher total peripheral resistance in older individuals, resulting from a loss of elasticity in the blood vessels. Because heart rate and systolic blood pressure are higher for any given level of exercise in the elderly, myocardial oxygen consumption, and thus rate-pressure product, will also be higher in older individuals than in younger adults.

Incremental Exercise to Maximum

Maximal cardiac output is lower in older individuals than in younger adults. This results from a lower maximal heart rate and a lower maximal stroke

Table 13.5

Cardiovascular Responses to Maximal Exercise in Young and Older Adults

Variable	Men 25 yr	Men 65 yr	Women 25 yr	Women 65 yr
$\dot{Q}$ (L·min^{-1})	25	16	18	12
SV (mL·b^{-1})	128	100	92	75
HR (b·min^{-1})	195	155	195	155
$\dot{V}O_2$ (L·min^{-1})	3.5	2.5	2.5	1.5
SBP (mmHg)	190	200	190	200
DBP (mmHg)	70	84	64	84
MAP (mmHg)	130	143	128	143
TPR (units)	5.2	8.9	7.1	11.9
RPP (units)	371	310	371	310

Source: Ogawa, et al. (1992).

volume. Maximal stroke volume decreases with advancing age, and the decline is of similar magnitude for both men and women, although women have a much smaller maximal stroke volume initially. Maximal heart rate decreases with age but does not vary significantly between the sexes. A decrease of approximately 10% per decade, starting at approximately age 30, has been reported for $\dot{V}O_2$max in sedentary adults (I. Åstrand, 1960; Heath, et al., 1981). Figures 13.13a and 13.13b depict the change in $\dot{V}O_2$max from childhood to age 75.

As with resting blood pressure, systolic and aerobic blood pressure responses to maximal exercise are typically higher in older individuals than in younger individuals of similar training (Ogawa, et al., 1992). Maximal systolic blood pressure may be 20–50 mmHg higher in older individuals, whereas maximal diastolic blood pressure may be 15–20 mmHg higher. As a result of an elevated systolic and diastolic blood pressure, mean arterial blood pressure is considerably higher at maximal exercise in the elderly than in younger adults.

Total peripheral resistance decreases during aerobic exercise in the elderly, but not to the same extent that it does in younger individuals. This difference is a consequence of the loss of elasticity of the connective tissue in the vasculature that accompanies aging. Since the decrease in maximal heart rate for older individuals is greater than the increase in maximal systolic blood pressure when compared with those variables for younger adults, older individuals have a lower rate-pressure product at maximal exercise than younger individuals have. Table 13.5 presents typical cardiovascular values at maximal exercise in young and old adults of both sexes.

Cardiovascular Responses to Static Exercise

Static work occurs repeatedly during daily activities, such as lifting and carrying heavy objects, and is a common form of activity encountered in many occupational settings, particularly manufacturing jobs where lifting is common. Additionally, a large number of sports and recreational activities have a static component associated with their performance. For example, weight-lifting, rowing, and racquet sports all involve static exercise. The magnitude of the cardiovascular response to static exercise is affected by several factors, but most noticeably by the intensity of muscle contraction.

Intensity of Muscle Contraction

The cardiovascular response to static exercise depends on the intensity of contraction, provided the contraction is held for a specified time period. The intensity of a static contraction is expressed as a percentage of maximal voluntary contraction (% MVC). Figure 13.17 illustrates the cardiovascular response to static contractions of the forearm (handgrip) muscles at 10, 20, and 50% MVC. Notice that at 10 and 20% MVC the contraction could be held for 5 min, but at 50% MVC the contraction could be held for only 2 min. Thus, as with aerobic exercise, intensity and duration are inversely related. Also note that the data presented in this figure are from handgrip exercises. Although the pattern of response appears to be similar for different muscle groups, the actual values may vary considerably depending on the amount of active muscle involved.

Cardiac output increases during static contractions owing to an increase in heart rate, with the magnitude of the increase dependent upon the intensity of exercise. Stroke volume (Figure 13.17b) remains relatively constant during low-intensity contractions and decreases during high-intensity contractions. There is a marked increase in stroke volume immediately following the cessation of high-intensity contractions (Lind, et al., 1964; Smith, et al., 1993). This is the same rebound rise in recovery as seen in a-$\dot{V}O_2$ diff, $\dot{V}_E$, and $\dot{V}O_2$ (Chapter 11). The reduction in stroke volume during high-intensity contractions is probably the result of both a decreased preload and an increased afterload. Preload is decreased because of high intrathoracic pressure, which compresses the vena cava and thus decreases the return of venous blood to the heart. Because arterial blood pressure is markedly elevated during static contractions (increased afterload), less blood will be ejected at a given force of contraction. Heart
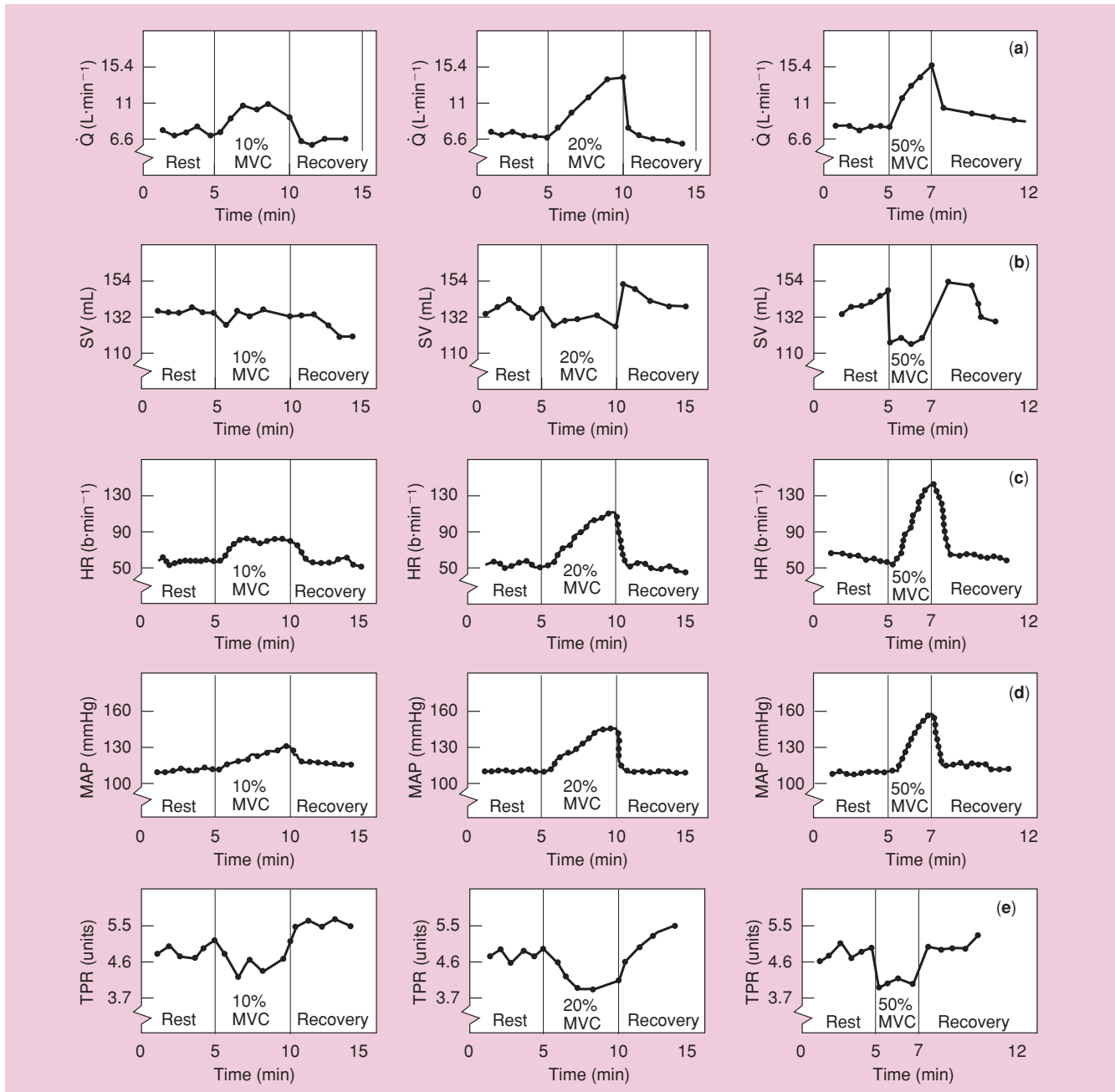
Figure 13.17
Cardiovascular Response to Varying Intensities
of Handgrip Exercise

rate (Figure 13.17c) increases during static exercise. The magnitude and the rate of the increase in heart rate depends on the intensity of contraction. The greater the intensity, the greater the heart rate response.

Static exercise is characterized by a rapid increase in both systolic pressure and diastolic pressure, termed the **pressor response,** which appears to be inappropriate for the amount of work produced by

Pressor Response The rapid increase in both systolic pressure and diastolic pressure during static exercise.

the contracting muscle (Lind, et al., 1964). Since both systolic and diastolic pressures increase in static exercise, there is a marked increase in mean arterial pressure (Figure 13.17d) (Donald, et al., 1967; Lind, et al., 1964; Seals, et al., 1985; Tuttle and Horvath, 1957). As in any muscular work, static exercise increases metabolic demands of the active muscle. However, in static work high intramuscular tension results in mechanical constriction of the blood vessels, which impedes blood flow to the muscle. The reduction in muscle blood flow during static exercise results in a buildup of local by-products of metabolism. These chemical by-products [H^+, adenosine diphosphate (ADP), and others] stimulate sensory nerve endings, which leads to a pressor reflex, causing a rise in mean arterial pressure (pressor response). This rise is substantially larger than the increase during aerobic exercise requiring similar energy expenditure (Asmussen, 1981; Hanson and Nagle, 1985). Notice in Figure 13.17d that holding a handgrip dynamometer at 20% MVC for 5 min results in an increase of 20–30 mmHg in mean arterial pressure and holding 50% MVC for 2 min caused a 50-mmHg increase in mean arterial pressure!

Total peripheral resistance, indicated by TPR in Figure 13.17e, decreases during static exercise, although not to the extent seen in dynamic aerobic exercise. The failure of resistance to decrease markedly helps to explain the higher blood pressure response to static contractions. The high blood pressure generated during static contractions helps overcome the resistance to blood flow owing to mechanical occlusion. Because systolic blood pressure and heart rate both increase during static exercise, there is a large increase in myocardial oxygen consumption and thus rate-pressure product.

Table 13.1 on page 362 summarizes cardiovascular responses to static exercise.

Blood Flow during Static Contractions

Blood flow to the working muscle is impeded during static contractions because of mechanical constriction of the blood vessel supplying the contracting muscle (Freund, et al., 1979; Sjogaard, et al., 1988). Figure 13.18 depicts blood flow in the quadriceps muscle when a 5% and 25% MVC contraction were held to fatigue. The 5% MVC load could be held for 30 min; the 25% load could be held for only 4 min. Quadriceps blood flow is greater during the 5% MVC, suggesting that at 25% MVC there is considerable impedance to blood flow. In fact, blood flow during the 25% MVC load was very close to resting levels despite the metabolic work done by the muscle. The response seen during recovery suggests that when contraction ceases, a mechanical occlusion to the muscle is
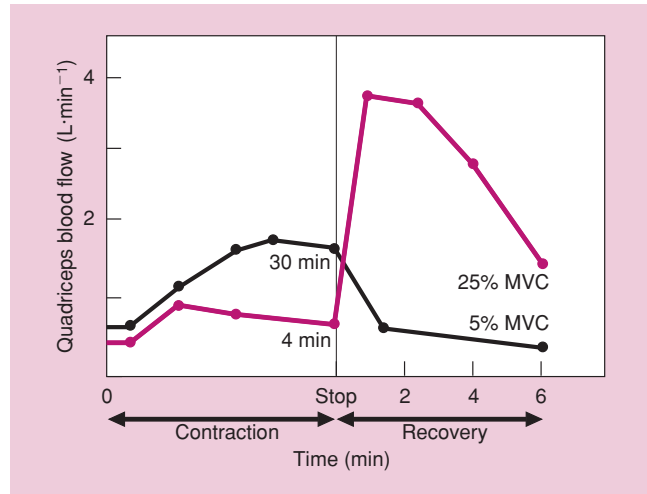

Figure 13.18
Blood Flow in the Quadriceps Muscle during Different Intensities of Contraction

Source: G. Sjogaard, G. Savard, & C. Juel. Muscle blood flow during isometric activity and its relation to muscle fatigue. *European Journal of Physiology.* 57:327–335 (1988). Reprinted by permission.

released. The marked increase in blood flow during recovery compensates for the reduced flow during sustained contraction. The relative force at which blood flow is impeded varies greatly among different muscle groups (Lind and McNichol, 1967; Rowell, 1993).

There is also mechanical constriction during dynamic aerobic exercise. However, the alternating periods of muscular contraction and relaxation that occur during rhythmical activity allow—and, indeed, encourage—blood flow, especially through the venous system.

Comparison of Aerobic and Static Exercise

Figure 13.19 compares the heart rate (13.19a) and blood pressure (13.19b) responses to fatiguing handgrip (static) exercise (30% MVC held to fatigue) and a maximal treadmill (dynamic aerobic) test to fatigue. Aerobic exercise (treadmill) is characterized by a large increase in heart rate, which contributes to an increased cardiac output. Aerobic exercise also shows a modest increase in systolic blood pressure and a relatively stable or decreasing diastolic blood pressure. Aerobic exercise is said to impose a "volume load" on the heart. Increased venous return leads to increased stroke volume, which contributes to an increased cardiac output. In contrast, fatiguing static exercise (handgrip) is characterized by a modest increase in heart rate but a dramatic increase in blood pressure (pressor response). Mean blood pressure increases as a result of increased systolic and diastolic blood
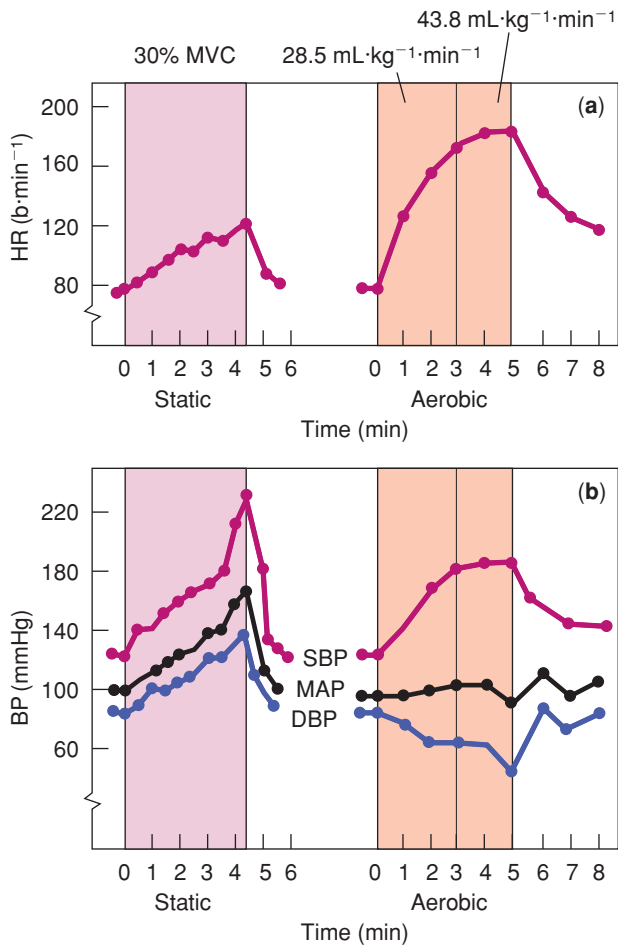
Figure 13.19

Comparison of Heart Rate and Blood Pressure Response to Static and Aerobic Exercise

Source: A. Lind. Cardiovascular responses to static exercise. *Circulation.* XLI(2) (1970). Reproduced with permission. Copyright 1970 American Heart Association.

Figure 13.20

Heart Rate and Blood Pressure Response of Males and Females to Static Exercise

Source: J. E. Misner, S. B. Going, B. H. Massey, T. E. Ball, M. G. Bemben, & L. K. Essandoh. Cardiovascular response in males and females to sustained maximal voluntary static muscle contraction. *Medicine and Science in Sports and Exercise.* 22(2):194–199 (1990). Reprinted by permission of Williams & Wilkins.

pressure. Static exercise is said to impose a "pressure load" on the heart. Increased mean arterial pressure means that the heart must pump harder to overcome the pressure in the aorta.

Sex Differences in Responses to Static Exercise

The heart rate response to static exercise (Figure 13.20a) is similar in males and females (Misner, et al., 1990). However, as shown in Figure 13.20b, when a group of young adult, healthy subjects held maximal contractions of the handgrip muscles for 2 min, the blood pressures reported for women were significantly lower than those reported for men (Misner, et al., 1990). Stroke volume and cardiac output responses in women during maximal static contraction of the finger flexors were similar to the responses
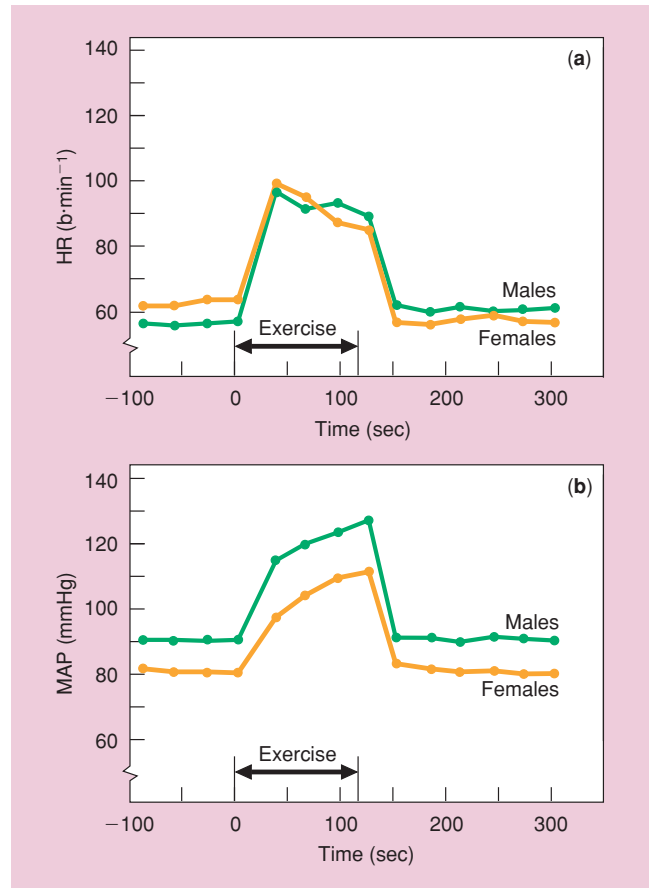
observed in the men, but no direct comparisons between men and women were made for these variables (Smith, et al., 1993). There are no comparable data available for boys and girls.

Cardiovascular Responses to Static Exercise in Older Adults

Many studies have described the cardiovascular responses to static exercise in the elderly (Goldstraw and Warren, 1980; Petrofsky and Lind, 1975; Sagiv, et al., 1988; VanLoan, et al., 1989). As an example, Figure 13.21 depicts the cardiovascular responses of young and old men to sustained handgrip and leg extension exercise over a range of submaximal static workloads (VanLoan, et al., 1989). Note that cardiac output (Figure 13.21a) and stroke volume

Figure 13.21

Cardiovascular Response of Males by Age to Static Exercise
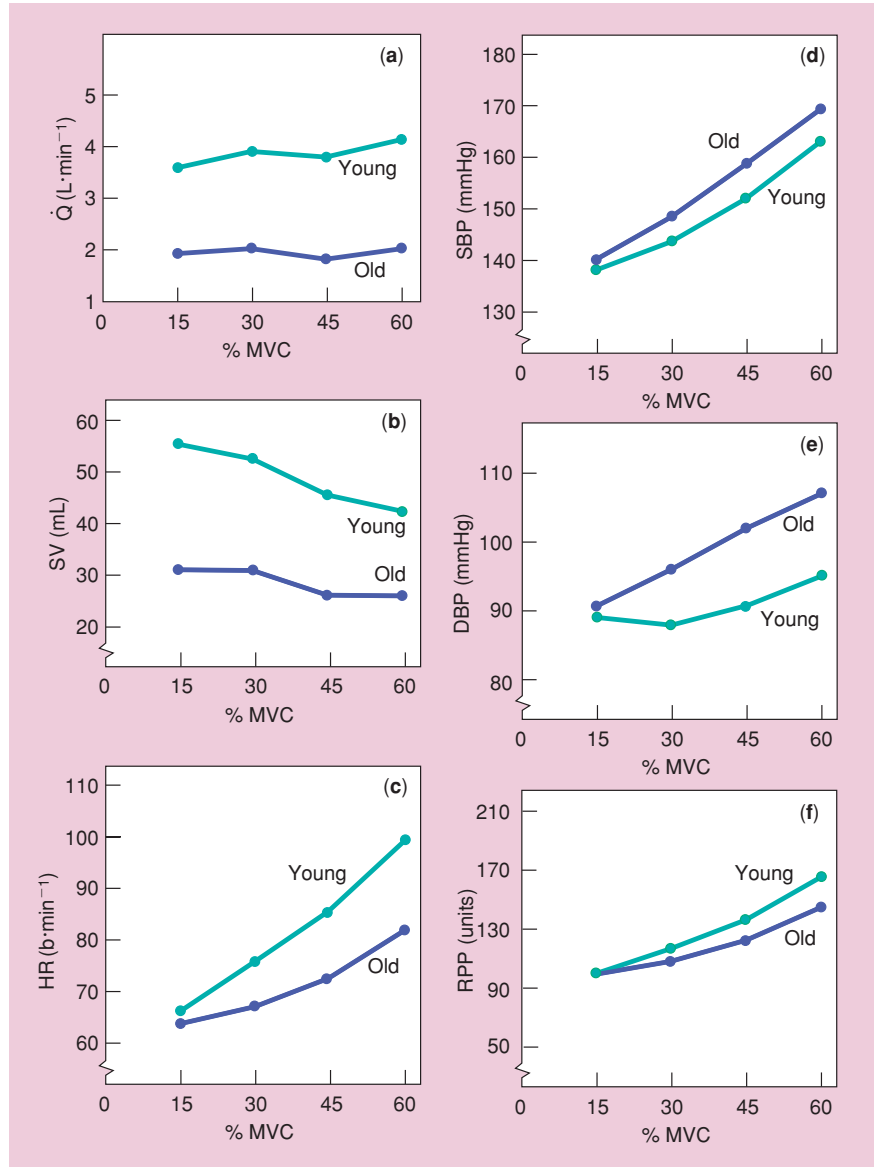
(Figure 13.21b) values are lower than normally reported owing to the measurement technique. However, concentrating on the relative differences between the responses of the young and older subjects reveals that cardiac output, stroke volume, and heart rate (Figure 13.21c) were lower for the older men than the younger men at each intensity. In contrast, blood pressure responses (Figures 13.21d and 13.21e) were higher for the older men at each intensity. As with dynamic aerobic exercise the differences in the cardiovascular responses between the two age groups are probably due to an age-related increase in resistance due to a loss of elasticity in the vasculature and a decreased ability of the myocardium to stretch and contract forcibly (VanLoan, et al., 1989). The rate-pressure product (Figure 13.21f) was higher for the younger subjects than for the older subjects at 30, 45, and 60% MVC. The small difference in rate-pressure product reflected a higher heart rate in younger subjects at each intensity of contraction, which was not completely offset by a lower systolic blood pressure in the younger subjects.

Cardiovascular Responses to Dynamic Resistance Exercise

Weight-lifting or resistance exercise includes a combination of dynamic and static contractions (Hill and Butler, 1991; MacDougall, et al., 1985). At the beginning of the lift, a static contraction exists until muscle force exceeds the load to be lifted and movement

occurs, which leads to a dynamic concentric (shortening) contraction as the lift continues. This is then followed by a dynamic eccentric (lengthening) contraction during the lowering phase (McCartney, 1999). Furthermore, there is always a static component associated with gripping the barbell. During dynamic resistance exercise there is a dissociation between the energy demand and the cardiorespiratory system. In contrast, during dynamic endurance activity the cardiorespiratory system is directly tied to the use of oxygen for energy production. In part, the reason for this dissociation between oxygen use and cardiovascular response to resistance exercise is that much of the energy required for resistance exercise comes from anaerobic (without oxygen) sources. Another important difference between resistance exercise and aerobic exercise that affects cardiovascular responses is the mechanical constriction of blood flow during resistance exercise because of the static nature of the contraction.

The magnitude of the cardiovascular response to resistance exercise depends on the intensity of the load (the weight lifted) and the number of repetitions performed.

Constant Repetitions/Varying Load

The cardiovascular responses also depend on the way in which the load and repetitions are combined. As expected, cardiovascular responses are greater when heavier loads are lifted, assuming the number of repetitions are held constant (Fleck, 1988; Fleck and Dean, 1987). For example, when subjects performed ten repetitions of three different weights (identified as light, moderate, and heavy), blood pressure was highest *at the completion* of the heaviest set (Wescott and Howes, 1983). Systolic blood pressure increased 16%, 22%, and 34% during the light, moderate, and heavy sets, respectively. Diastolic blood pressure, measured by auscultation, did not change significantly with any of the sets. There is disagreement about the diastolic blood pressure response to resistance exercise; some authors report an increase and others report no change (Fleck, 1988; Fleck and Dean, 1987; Wescott and Howes, 1983). These discrepancies may reflect differences in measurement techniques (namely, auscultation and intra-arterial assessment) and timing of the measurement.

Resistance Exercise to Fatigue

A different pattern of response is seen when a given load is performed to fatigue. In this case the individual is performing maximal work regardless of the load. Figure 13.22 shows the cardiovascular
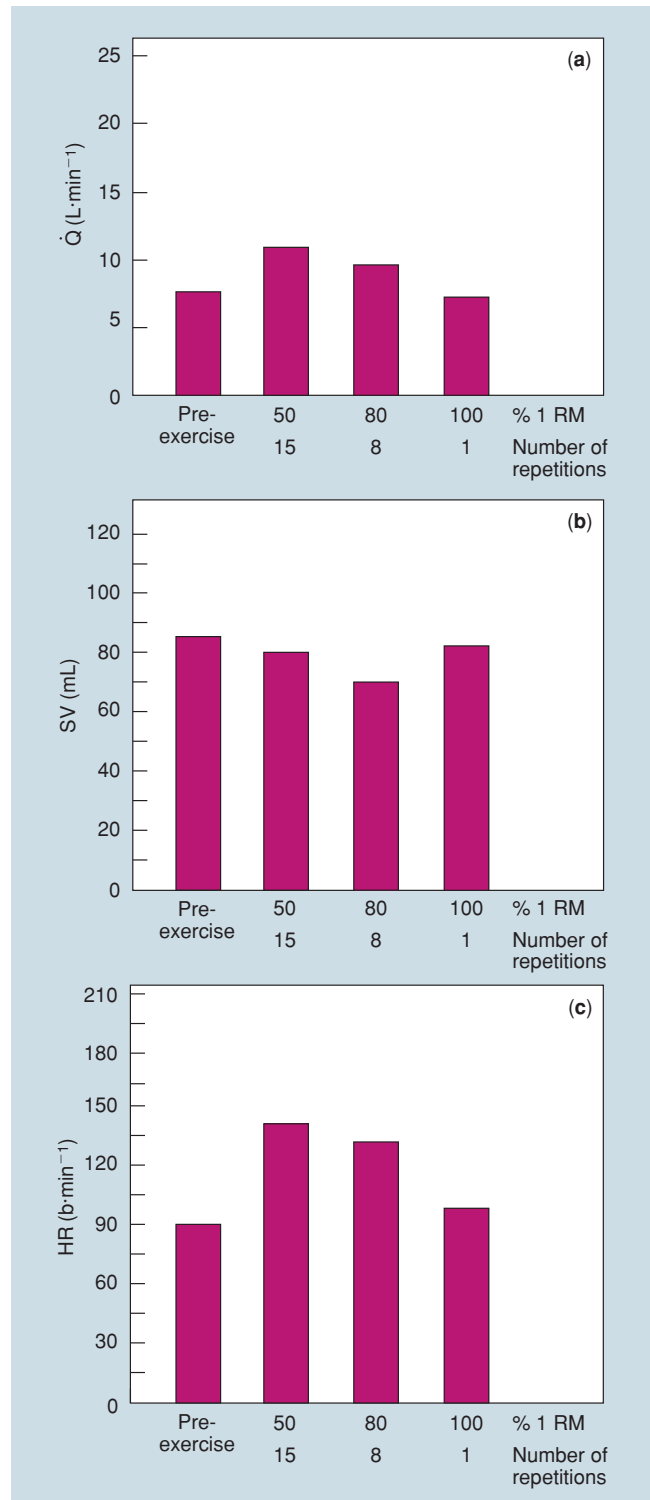

Figure 13.22
Cardiovascular Response at the Completion of Fatiguing Resistance Exercise (concentric knee extension exercise)

Source: Based on data from Falkel, et al. (1992).

Focus on Application

Variable	Snow Shoveling	Snow Blower	Treadmill (max)
Heart rate (b·min^{-1})	175 $\pm$ 15	124 $\pm$ 18	179 $\pm$ 17
Systolic blood pressure (mmHg)	198 $\pm$ 17	161 $\pm$ 14	181 $\pm$ 25
Rate-pressure product	347	199.6	324
$\dot{V}O_2$(mL·kg^{-1}min^{-1})	19.95 $\pm$ 2.8	8.4 $\pm$ 2.5	32.55 $\pm$ 6.3
Rating of perceived exertion	16.7 $\pm$ 1.7	9.9 $\pm$ 1.0	17.9 $\pm$ 1.5

✳ Cardiovascular Demands of Shoveling Wet, Heavy Snow

As the text has described, upper-body exercise is associated with greater cardiovascular strain (exemplified by higher heart rates and higher blood pressures at any given submaximal level of oxygen consumption) than lower-body exercise. Similarly, it was emphasized that both static and dynamic resistance exercise are characterized by modest increases in heart rate but exaggerated increases in blood pressure. Snow shoveling presents the shoveler with the unique combination of a predominantly upper-body activity that has both static and dynamic components. In addition, snow shoveling is always done in the cold (and sometimes in frigid conditions), and often when the individual is under the added stress of digging out to get somewhere on time. It is not unusual to hear about individuals collapsing and dying of heart attacks while clearing snow.

Franklin and his colleagues performed an experiment to determine the specific demands of snow shoveling on the heart. Ten sedentary, healthy, young adult males cleared two 15-m paths of wet, heavy snow that was 5–13 cm deep outside in the cold (2 degrees C) for 10 min. For one trial they used a 1.4 kg plastic shovel. They were told to repeatedly lift-throw the snow to the side at a self-selected rate. The group mean was 12 $\pm$ 2 loads per minute at approximately 7.3 kg per load for a total of 872.7 kg (1920 lb) over the 10-min time span. For the second trial they used a motorized snow blower. Ten to 15 min of rest was permitted between the randomly assigned trials. On another day, each participant underwent a treadmill maximal oxygen consumption test in the laboratory. The results are presented in the accompanying table.

After only 2 min of snow shoveling, the subjects' average heart rate was 85% of the treadmill HRmax. The HR continued to increase until it reached 98% HRmax. Systolic blood pressure during the snow shoveling exceeded the treadmill maximum by 9.3%. The total body oxygen consumption was only 61.3% $\dot{V}O_2$max, but the myocardial oxygen consumption, as indicated by the rate-pressure product, was 107% of that required during maximal treadmill work. The disproportionate increase in myocardial oxygen demand relative to total body oxygen demand during shoveling was attributed to several factors: a reduced myocardial efficiency of arm exercise, a large static exercise component, the Valsalva maneuver, and the inhalation of cold air that could cause a spasm or constriction in the coronary arteries. These results clearly indicate that shoveling wet, heavy snow even for a short time period (10 min) places a tremendous physiological demand on the heart.

By comparison, using the snow blower resulted in elevations to only 69% HRmax, 89% maximal systolic blood pressure, 25% $\dot{V}O_2$max, and 61% maximal myocardial oxygen consumption, as reflected by the rate-pressure product. Whereas the manual shoveling was perceived as "very heavy" work, using the snow blower resulted in a "fairly light" rating.

The healthy, but untrained subjects in this study completed the shoveling without any adverse cardiac or musculoskeletal complications. Such work, especially if continued for 20–60 min would provide a heavy but acceptable workout. However, these results suggest that individuals with a history of heart disease, symptoms suggestive of cardiac disorder (dizziness, chest pain, abnormal electrocardiograms) or one or more major coronary risk factor (see Chapter 16) should avoid the work, or take precautions when faced with the task of clearing wet, heavy snow. These precautions include:

1. Take frequent breaks or use a work–rest approach.
2. Use both arms and legs in the lift-throw action.
3. Regulate body temperature with a hat, scarf over the mouth, and layers that can easily be added or removed.
4. Avoid large meals, alcohol consumption, and smoking immediately before and after shoveling.
5. Consider using a motorized snow blower.

Sources:

Franklin (1997); Franklin, et al. (1995).

response at the completion of leg extension exercise performed to fatigue. Subjects performed 50%, 80%, and 100% of their one repetition maximum (1 RM) as many times as they could, and cardiovascular variables were recorded at the end of each set (Falkel, et al., 1992). Subjects could perform the 100% load only one time, of course; but they could perform the 80% and 50% loads an average of 8 and 15 times, respectively. Thus, the greatest volume of work was performed when the lightest load was lifted the greatest number of times. Cardiac output *at the completion* of the set was highest when the lightest load was lifted for the greatest number of repetitions (Figure 13.22a).

The stroke volume achieved at the end of a set was similar for each condition (Figure 13.22b) and was slightly below resting levels. This is in contrast to significant increases in stroke volume measures typically obtained during aerobic exercise. Thus, dynamic resistance exercise does not produce the stroke volume overload that dynamic endurance exercise does (Hill and Butler, 1991; McCartney, 1999).

Heart rate was highest after completion of the set using the lightest load and lifting it the greatest number of times (Figure 13.22c). Heart rate was lowest when the single repetition using the heaviest weight was performed. Heart rates between 130 and 160 b·min^{-1} have been reported during resistance exercise (Hill and Butler, 1991). There is some evidence that the heart rate and blood pressure attained at fatigue are the same when loads between 60% and 100% of 1 RM are used, regardless of the number of times the load can be performed (Nau, et al., 1990).

When the load is heavy, MAP and HR increase gradually with succeeding repetitions in a set to failure (Fleck and Dean, 1987; MacDougall, et al., 1985). Figure 13.23a shows the mean arterial blood pressure, measured intra-arterially, *during a set* of leg press exercises that represented 95% of one repetition maximum, and Figure 13.23b shows the heart rate during these exercises. In this study peak systolic blood pressure averaged 320 mmHg, and peak diastolic blood pressure averaged 250 mmHg! The dramatic increase in blood pressure during dynamic resistance exercise results from the mechanical compression on the blood vessels and performance of the Valsalva maneuver (as explained in Chapter 11). Total peripheral resistance is higher during dynamic resistance exercise than during dynamic aerobic exercise because of the vasoconstriction caused by the pressor reflex. In fact, some studies have reported a slight increase in total peripheral resistance during resistance exercise, rather than the decrease that is observed with aerobic exercise (Lentini, et al., 1993;
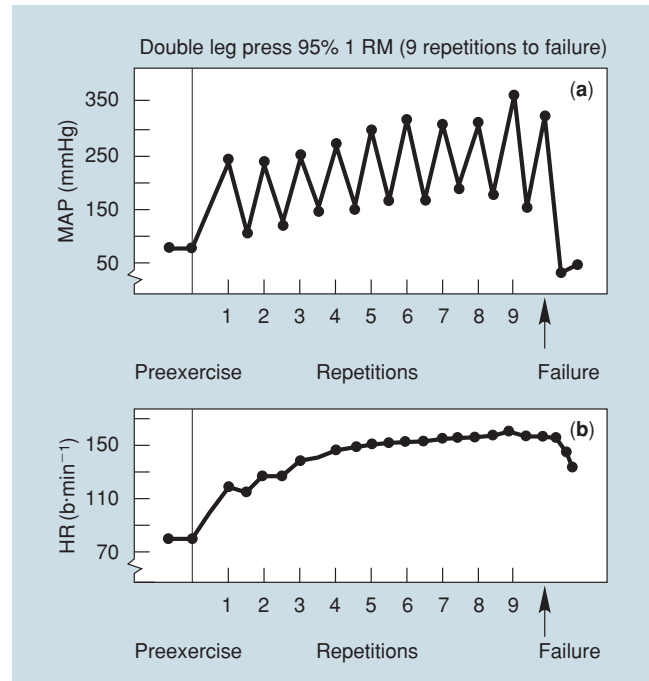

Figure 13.23
Heart Rate and Blood Pressure Response during a Set of Resistance Exercise

McCartney, 1999; Miles, et al., 1987). Myocardial oxygen consumption and, thus, the rate-pressure product can reach extremely high levels because of the tachycardia and exaggerated systolic blood pressure response. Dynamic resistance exercise causes large (about 15%) but transient decreases in plasma volume (Hill and Butler, 1991). The cardiovascular response of children to resistance exercise is similar to that of adults, with heart rate and blood pressure increasing progressively throughout a set (Nau, et al., 1990).

A summary of cardiovascular responses to resistance exercise is included in Table 13.1 on page 362.

Summary

1. During short-term, light to moderate aerobic exercise, cardiac output, stroke volume, heart rate, systolic blood pressure, and rate-pressure product increase rapidly at the onset of exercise and reach steady state within approximately 2 min. Diastolic blood pressure remains relatively unchanged, and resistance decreases rapidly and then plateaus.

2. During long-term, moderate to heavy aerobic exercise, cardiac output, stroke volume, heart rate, systolic blood pressure, and rate-pressure product increase rapidly. Once steady state is achieved, cardiac output remains relatively constant owing to the downward drift of stroke volume and the upward drift of heart rate. Systolic blood pressure and resistance may also drift downward during prolonged, heavy work. This cardiovascular drift is associated with rising body temperature.

3. During incremental exercise to maximum, cardiac output, heart rate, systolic blood pressure, and rate-pressure product increase in a rectilinear fashion with increasing workload. Stroke volume increases initially and then plateaus at a workload corresponding to approximately 40–50% of $\dot{V}O_2$ max in normally active adults and children. Diastolic blood pressure remains relatively constant throughout an incremental exercise test. Resistance decreases rapidly with the onset of exercise and reaches its lowest value at maximal exercise.

4. The decrease in resistance that accompanies aerobic exercise has two important implications. First, the decrease in resistance allows greater blood flow to the working muscles. Second, the decrease in resistance keeps blood pressure from rising excessively. The increase in cardiac output would produce a much greater rise in blood pressure if it were not for the fact that there is a simultaneous decrease in resistance.

5. Blood volume decreases during aerobic exercise. The majority of the decrease occurs within the first 10 min of activity and depends on exercise intensity. A decrease of 10% of blood volume is not uncommon.

6. Stroke volume initially increases during dynamic aerobic exercise and then plateaus at a level that corresponds to 40–50% of $\dot{V}O_2$max. The increase in stroke volume results from changes in left ventricular end–diastolic volume and left ventricular end–systolic volume. Left ventricular end–diastolic volume increases primarily because the active muscle pump returns blood to the heart. Left ventricular end–systolic volume decreases owing to augmented contractility of the heart, thus ejecting more blood and leaving less in the ventricle.

7. The pattern of cardiovascular response is the same for both sexes. However, males have a higher cardiac output, stroke volume, and systolic blood pressure at maximal exercise. Additionally, males have a higher $\dot{V}O_2$max. Most of these differences are attributable to differences in body size and heart size between the sexes and to the greater hemoglobin concentration of males.

8. The pattern of cardiovascular response in children is similar to the adult response. However, children have a lower cardiac output, stroke volume, and systolic blood pressure at an absolute workload and at maximal exercise. Most of these differences are attributable to differences in body size and heart size.

9. As adults age, their cardiovascular responses change. Maximal cardiac output, stroke volume, heart rate, and $\dot{V}O_2$max decrease. Maximal systolic blood pressure, diastolic blood pressure, and mean arterial pressure increase.

10. Static exercise is characterized by modest increases in heart rate and cardiac output and exaggerated increases in systolic blood pressure, diastolic blood pressure and mean arterial pressure, known as the pressor response.

11. Dynamic resistance exercise results in a modest increase in cardiac output, an increase in heart rate, little change or a decrease in stroke volume, and a large increase in blood pressure.

Review Questions

1. Graph and explain the pattern of response for each of the major cardiovascular variables during short-term, light to moderate aerobic exercise. Explain the mechanisms responsible for each response.

2. Graph and explain the pattern of response for each of the major cardiovascular variables during long-term, moderate to heavy aerobic exercise. Explain the mechanisms responsible for each response.

3. Graph and explain the pattern of response for each of the major cardiovascular variables during incremental aerobic exercise to maximum. Explain the mechanisms responsible for each response.

4. Graph and explain the pattern of response for each of the major cardiovascular variables during static exercise. Explain the mechanisms responsible for each response.

5. Graph and explain the pattern of response for each of the major cardiovascular variables during dynamic resistance exercise. Explain the mechanisms responsible for each response.

6. Discuss the change that occurs in total peripheral resistance during exercise, and explain its importance for blood flow and blood pressure. Why is resistance altered in older adults?

7. Describe the pressor response to static exercise, and explain the mechanisms by which blood pressure is elevated.

For further review and additional study tools, go to thePoint.lww.com/Plowman and view the Student Study Guide for Exercise Physiology for Health, Fitness, and Performance *by Sharon A. Plowman and Denise L. Smith.*

Passport to the Internet

Visit the following Internet sites to explore further topics and issues related to understanding cardiovascular response to exercise. To visit an organization's web site, go to www.physiologyplace.com and click on "Passport to the Internet."

The American College of Sports Medicine Home page of the professional organization for individuals in sports medicine and exercise science. Spend some time exploring this site and discovering the multitude of resources available.

Masters Athlete Physiology & Performance This site is the springboard to an ever-growing body of literature on the physiological basis for endurance performance and training. Many exercise physiologists started out as athletes whose desire for better performance drove them to explore how the human machine worked. This site begins with the basics and allows the reader to explore topics in greater depth.

The American Heart Association Visit one of the most complete sites for the latest information on cardiorespiratory health promotion. Investigate the latest findings and ongoing research dedicated to understanding cardiovascular disease. While there, go to www.choosetomove.org and investigate this special program dedicated to helping women establish physical activity as a habit.

The Nicholas Institute of Sports Medicine and Athletic Trauma (NISMAT) The Nicholas Institute of Sports Medicine and Athletic Trauma (NISMAT) is the first hospital-based facility dedicated to the study of sports medicine in the United States. This site has various resources related to cardiovascular and muscular issues.

Inner Learning Online This interactive web site contains an inner exploration of the human anatomy. Each topic has animations, graphics, and numerous descriptive links.

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