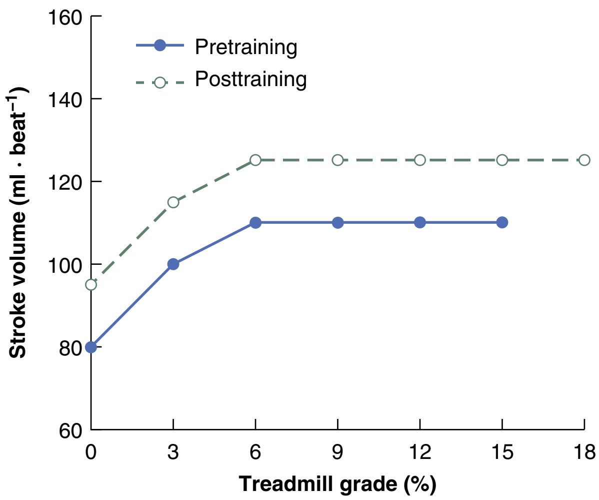

FIGURE 4.17 SV increases with training due to larger volume of the ventricle (19).

RESEARCH INSIGHT

Stroke Volume in Elite Athletes

For most people, SV levels off at about 40% $\dot{V}O_2$max, making HR the sole factor increasing blood flow to the muscles at higher exercise intensities. However, there is clear evidence that this is not the case for highly trained endurance athletes. Interestingly, in these athletes, SV increases systematically with exercise intensity up to $\dot{V}O_2$max. This appears to be due to both enhanced filling of the ventricle before contraction (EDV) and greater emptying of the ventricle during contraction (ejection fraction), in contrast to what is observed in people of average fitness (25, 69).

Cardiac Output

Cardiac output (***Q***) is the volume of blood pumped by the heart per minute and is calculated by multiplying the HR (beats · min $^{-1}$) by the SV (ml · beat^{-1}).

$$\text{Cardiac output} = \text{HR} \cdot \text{SV}$$
$$= 60 \text{ beats} \cdot \text{min}^{-1} \cdot 80 \text{ ml} \cdot \text{beat}^{-1}$$
$$= 4{,}800 \text{ ml} \cdot \text{min}^{-1}, \text{ or } 4.8 \text{ L} \cdot \text{min}^{-1}.$$

Cardiac output increases linearly with work rate. Generally, the cardiac output response to light and moderate work is not affected by endurance training. What changes is how the cardiac output is achieved: with a lower HR and higher SV.

Maximal cardiac output (highest value reached in a GXT) is the most important cardiovascular variable determining maximal aerobic power because the oxygen-enriched blood (carrying about 0.2 L of O_2 per liter of blood) must be delivered to the muscle for the mitochondria to use. If a person's maximal cardiac output is 10 L · min^{-1}, only 2 L of O_2 would leave the heart each minute (i.e., 0.2 L of O_2 per liter of blood times a cardiac output of 10 L · min^{-1} = 2 L of O_2 · min^{-1}). A person with a maximal cardiac output of 30 L· min^{-1} would deliver 6 L of O_2 · min^{-1} to the tissues. Endurance training increases the maximal cardiac output and thus the delivery of oxygen to the muscles (see figure 4.18). This increase in maximal cardiac output is matched by greater capillary numbers in the muscle to allow the blood to move slowly enough through the muscle to maintain the time needed for oxygen to diffuse from the blood to the mitochondria (62). The increase in maximal cardiac output accounts for 50% of the increase in maximal oxygen uptake that occurs in previously sedentary people who engage in endurance training (59).

Oxygen Extraction

Two factors determine oxygen uptake at any time: the volume of blood delivered to the tissues per minute (cardiac output) and the volume of oxygen extracted from each liter of blood. Oxygen extraction is calculated by subtracting the oxygen content of mixed venous blood (as it returns to the heart) from the oxygen content of the arterial blood. This is the **arteriovenous oxygen difference**, or the *(a − v̄o) O_2 difference.*

$$\dot{V}O_2 = \text{cardiac output} \cdot (a - v\bar{o})O_2 \text{ difference.}$$

At rest, cardiac output = 5 L · min^{-1},
arterial oxygen content = 200 ml of O_2 · L^{-1}, and
mixed venous oxygen content = 150 ml of O_2 · L^{-1}.

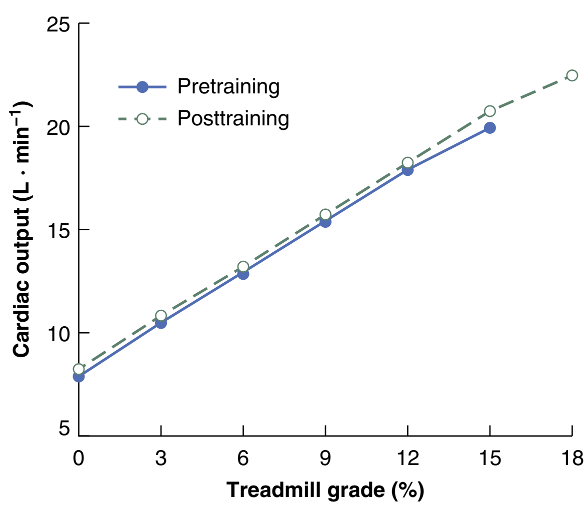

FIGURE 4.18 Maximal cardiac output increases following training (19).