

patients with ischemic heart disease and limited myocardial O₂ supply. Treatment with vasodilators has the opposite effect; when afterload falls, cardiac output rises (**Chap. 257**).

Under normal circumstances, the various influences acting on cardiac performance interact in a complex fashion to maintain cardiac output at a level responsive to the requirements of tissue metabolic demands (**Fig. 237-10**). Interference with a single mechanism may not influence the cardiac output due to homeostatic adjustments. For example, a moderate reduction of blood volume or the loss of the atrial contribution to ventricular contraction can be tolerated without a reduction in resting cardiac output. Under these circumstances, other factors, such as adrenergic neuronal impulses increasing cardiac contractility, heart rate, and venous tone, will serve as compensatory mechanisms and sustain cardiac output in a normal individual. Ultimately, understanding the complex interactions between these different variables requires rigorous models to predict relevant outcomes, and led to the early application of systems engineering principles in medicine.

■ EXERCISE

The integrated response to exercise illustrates typical interactions among the three determinants of stroke volume: preload, afterload, and contractility (**Fig. 237-9**). Hyperventilation, the pumping action of the exercising muscles, and venoconstriction during exercise all augment venous return and hence ventricular filling and preload (**Table 237-2**). Simultaneously, the increase in neuronal and humoral adrenergic stimulation of the myocardium and the tachycardia that occur during exercise combine to augment the myocardial contractility (**Fig. 237-9**, curves 1 and 2), together elevating stroke volume and stroke work, with little or no change in end-diastolic pressure and volume (**Fig. 237-9**, points A and B). Vasodilation occurs in the exercising muscles, thus limiting the increase in afterload that otherwise would occur as cardiac output rises to levels as high as five times greater than basal levels during maximal exercise. This vasodilation ultimately allows the achievement of elevated cardiac outputs during exercise at arterial pressures only moderately higher than the resting state.