Cardiac cycle and heart sound
Cardiac output

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LEARNING OUTCOMES

As a result of the lesson you will be able to:

- *Describe the relationship between blood pressure and blood flow*
- *Summarize and explain the connection between the various events of the cardiac cycle*
- *Compare atrial and ventricular systole and diastole*
- *Relate heart sounds detected by auscultation to action of heart's valves*
- *Define cardiac output and Describe factors that effect cardiac output and be able to calculate it*
- *Identify cardiovascular centers and cardiac reflexes that regulate heart function*
- *Summarize factors affecting stroke volume, heart rate and cardiac output;*

Cardiac Cycle

- **cardiac cycle** - one complete contraction and relaxation of all four chambers of the heart
- atrial **systole** (contraction) occurs while ventricles are in **diastole** (relaxation)
- atrial **diastole** occurs while ventricles in **systole**
- **quiescent period** all four chambers relaxed at same time
- questions to solve – *how does pressure affect blood flow?* and *how are heart sounds produced?*

Principles of Pressure and Flow

- two main variables that govern fluid movement:
- **pressure -** causes a fluid to flow (fluid dynamics)
  - pressure gradient - pressure difference between two points
  - measured in mm Hg with a manometer or sphygmomanometer
- **resistance -** opposes fluid flow
  - great vessels have positive blood pressure
  - ventricular pressure must rise above this resistance for blood to flow into great vessels

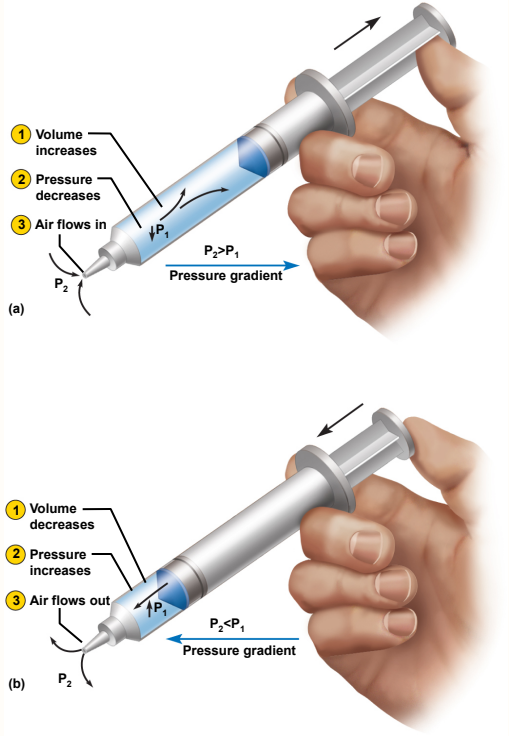


Figure 19.18

Pressure Gradients and Flow

- fluid flows only if it is subjected to more pressure at one point than another which creates a **pressure gradient**
  - fluid flows **down its pressure gradient** from high pressure to low pressure
- events occurring on left side of heart
  - when ventricle relaxes and expands, its internal pressure falls
  - if bicuspid valve is open, blood flows into left ventricle
  - when ventricle contracts, internal pressure rises
  - AV valves close and the aortic valve is pushed open and blood flows into aorta from left ventricle
- opening and closing of valves are governed by these pressure changes
  - AV valves limp when ventricles relaxed
  - semilunar valves under pressure from blood in vessels when ventricles relaxed

Operation of Heart Valves

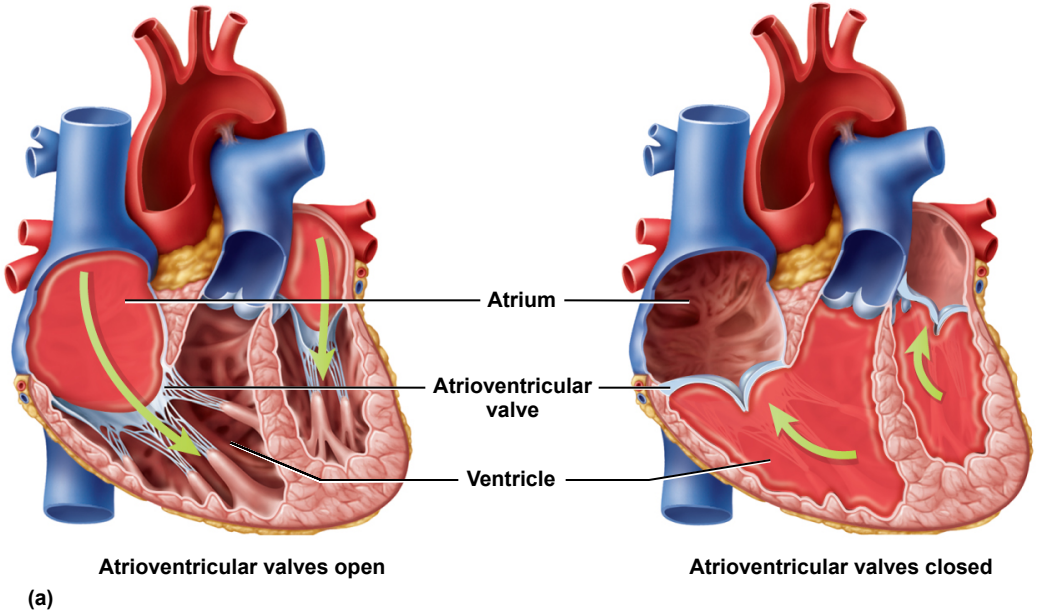


Figure 19.19

Valvular Insufficiency

- **valvular insufficiency** (incompetence) - any failure of a valve to prevent reflux (regurgitation) the backward flow of blood
  - **valvular stenosis** – cusps are stiffened and opening is constricted by scar tissue
    - result of **rheumatic fever** autoimmune attack on the mitral and aortic valves
    - heart overworks and may become enlarged
    - **heart murmur** – abnormal heart sound produced by regurgitation of blood through incompetent valves
  - **mitral valve prolapse** – insufficiency in which one or both mitral valve cusps bulge into atria during ventricular contraction
    - hereditary in 1 out of 40 people
    - may cause chest pain and shortness of breath

Heart Sounds

- **auscultation** - listening to sounds made by body
- **first heart sound** (S_1), louder and longer “lubb”, occurs with closure of AV valves, turbulence in the bloodstream, and movements of the heart wall
- second heart sound (S_2), softer and sharper “dupp” occurs with closure of semilunar valves, turbulence in the bloodstream, and movements of the heart wall
- S_3 - rarely heard in people over 30
- exact cause of each sound is not known with certainty

Phases of Cardiac Cycle

- ventricular filling
- isovolumetric contraction
- ventricular ejection
- isovolumetric relaxation

- all the events in the cardiac cycle are completed in less than one second!

Ventricular Filling

- during diastole, ventricles expand
  - their pressure drops below that of the atria
  - AV valves open and blood flows into the ventricles
- **ventricular filling** occurs in three phases:
  - **rapid ventricular filling** - first one-third
    - blood enters very quickly
  - **diastasis** - second one-third
    - marked by slower filling
    - P wave occurs at the end of diastasis
  - **atrial systole** - final one-third
    - atria contract
- **end-diastolic volume** (EDV) – amount of blood contained in each ventricle at the end of ventricular filling
  - **130 mL of blood**

Isovolumetric Contraction

- **atria repolarize** and relax
  - remain in diastole for the rest of the cardiac cycle
- **ventricles depolarize**, create the QRS complex, and begin to contract
- **AV valves close** as ventricular blood surges back against the cusps
- **heart sound S_1** occurs at the beginning of this phase
- '**isovolumetric**' because even though the ventricles contract, they do not eject blood
  - because pressure in the aorta (80 mm Hg) and in pulmonary trunk (10 mm Hg) is still greater than in the ventricles
- cardiocytes exert force, but with all four valves closed, the blood cannot go anywhere

Ventricular Ejection

- ejection of blood begins when the ventricular pressure exceeds arterial pressure and forces semilunar valves open
  - pressure peaks in left ventricle at about 120 mm Hg and 25 mm Hg in the right
- blood spurts out of each ventricle rapidly at first – **rapid ejection**
- then more slowly under reduced pressure – **reduced ejection**
- ventricular ejections last about 200 – 250 msec
  - corresponds to **the plateau phase of the cardiac action potential**
- **T wave** occurs late in this phase
- **stroke volume (SV)** of about **70 mL** of blood is ejected of the 130 mL in each ventricle
  - **ejection fraction** of about 54%
  - as high as 90% in vigorous exercise
- **end-systolic volume (ESV)** – the **60 mL** of blood left behind

Isovolumetric Relaxation

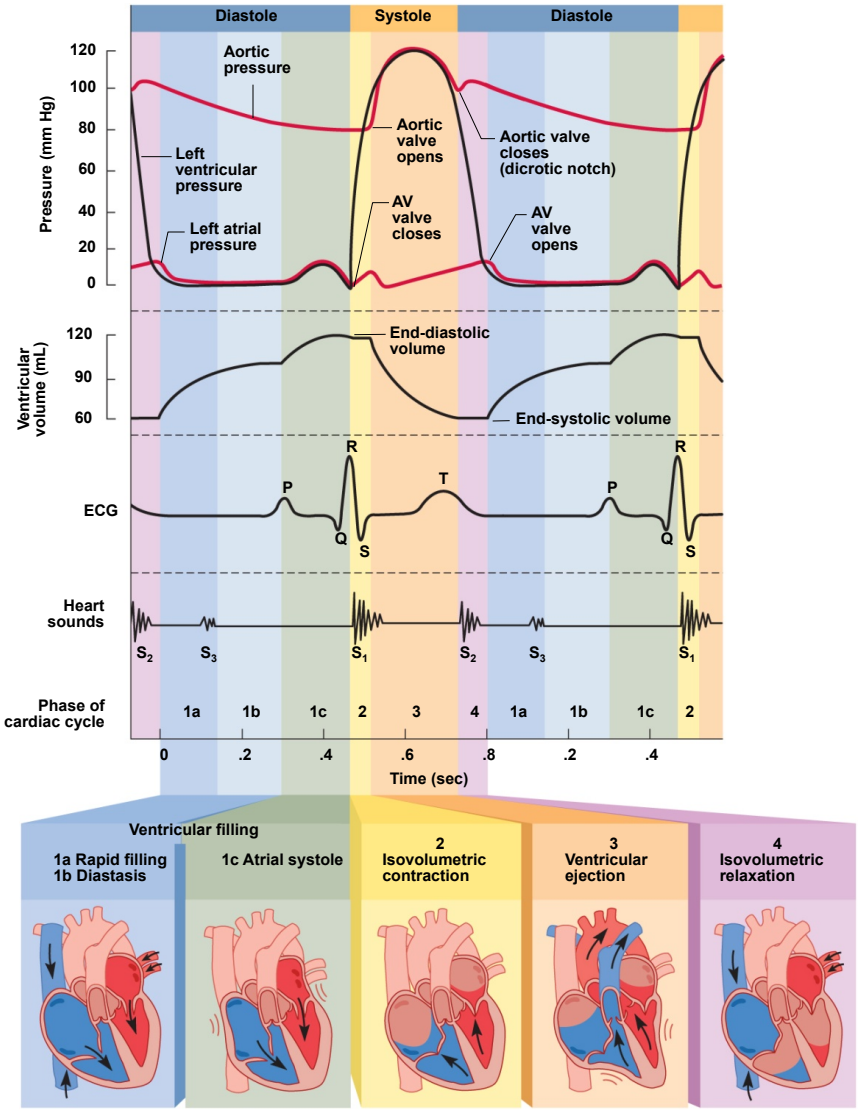
- early **ventricular diastole**
  - when **T wave ends** and **the ventricles begin to expand**
- elastic recoil and expansion would cause pressure to drop rapidly and suck blood into the ventricles
  - blood from the aorta and pulmonary briefly **flows backwards**
  - **filling the semilunar valves** and **closing the cusps**
  - creates a **slight pressure rebound** that appears as the **dicrotic notch** of the aortic pressure curve
  - **heart sound S_2** occurs as blood rebounds from the closed semilunar valves and the ventricle expands
  - '**isovolumetric**' because semilunar valves are closed and AV valves have not yet opened
    - ventricles are therefore taking in no blood
  - when AV valves open, ventricular filling begins again

Timing of Cardiac Cycle

- in a resting person
  - **atrial systole** last about **0.1 sec**
  - **ventricular systole** about **0.3 sec**
  - **quiescent period**, when all four chambers are in diastole, **0.4 sec**

- **total duration of the cardiac cycle** is therefore **0.8 sec** in a heart beating **75 bpm**

Major Events of Cardiac Cycle



- ventricular filling
- isovolumetric contraction
- ventricular ejection
- isovolumetric relaxation

Figure 19.20

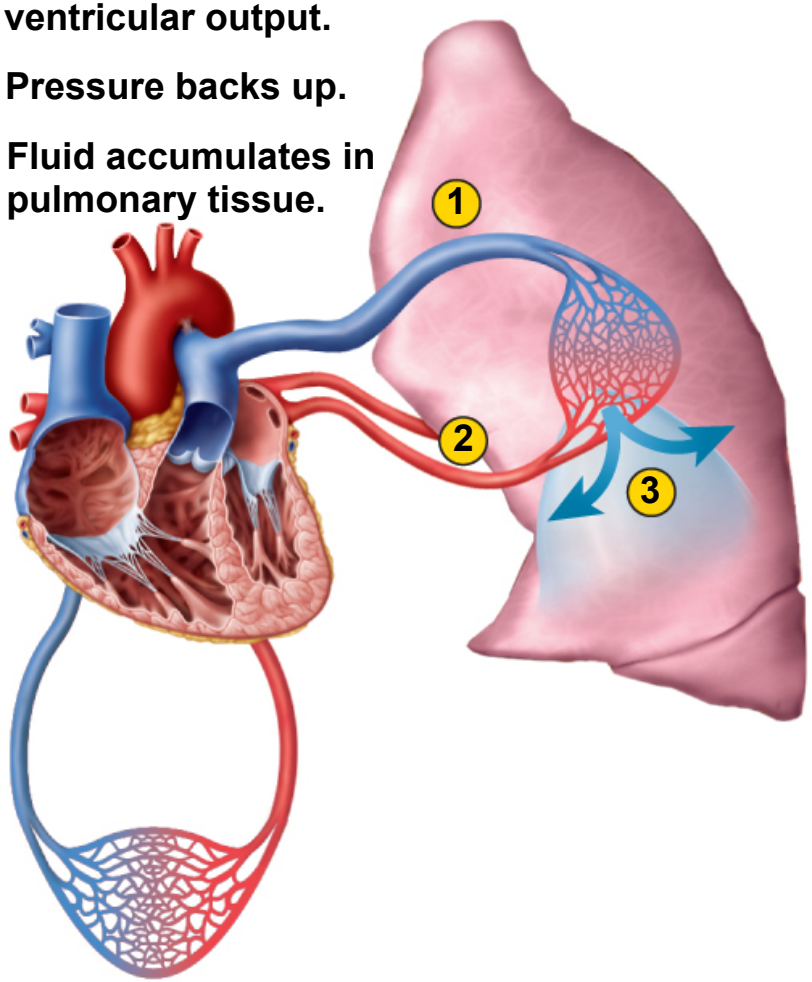
Overview of Volume Changes

end-systolic volume (ESV)	**60 ml**
-passively added to ventricle during atrial diastole	+30 ml
-added by atrial systole	+40 ml
total: **end-diastolic volume (EDV)**	**130 ml**
stroke volume (SV) ejected by ventricular systole	**-70 ml**
leaves: **end-systolic volume (ESV)**	**60 ml**

both ventricles must eject same amount of blood

Unbalanced Ventricular Output

1. **Right ventricular output exceeds left ventricular output.**
2. **Pressure backs up.**
3. **Fluid accumulates in pulmonary tissue.**

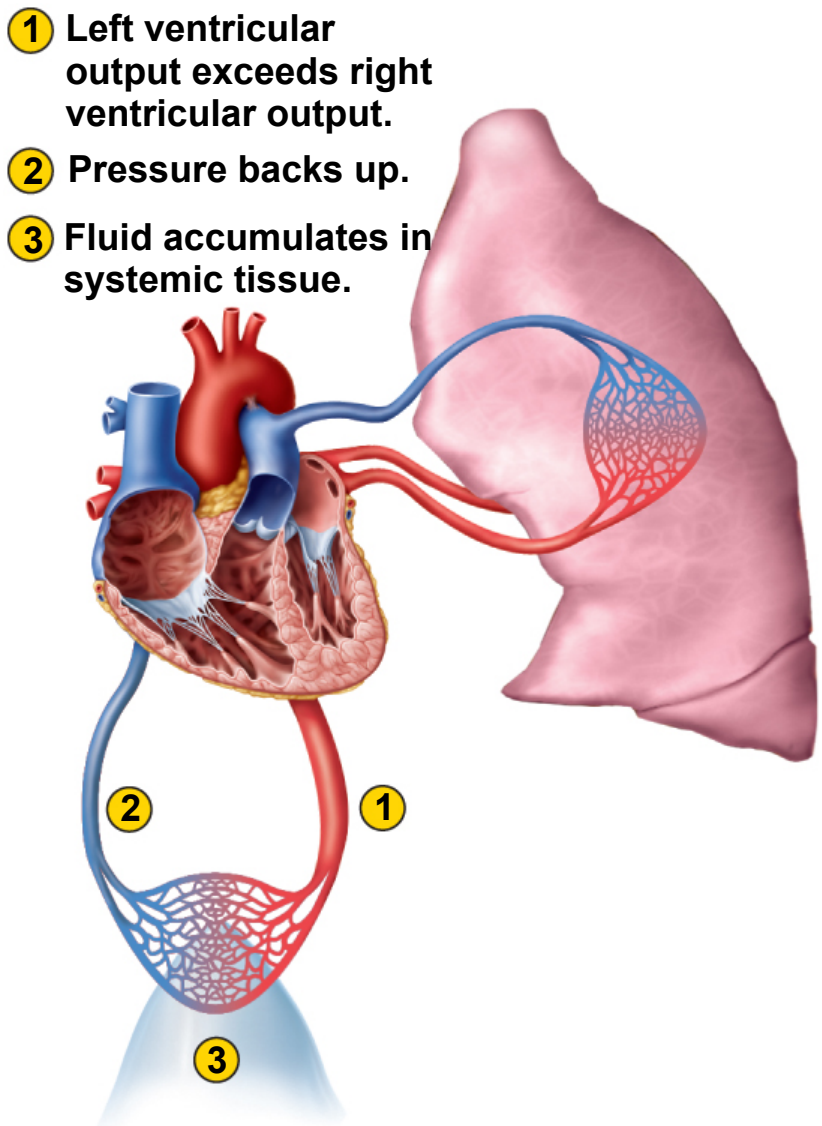


(a) Pulmonary edema

pulmonary edema

Figure 19.21a

Unbalanced Ventricular Output



(b) Systemic edema

peripheral edema

Figure 19.21b

Congestive Heart Failure

- **congestive heart failure** (CHF) - results from the failure of either ventricle to eject blood effectively
  - usually due to a heart weakened by myocardial infarction, chronic hypertension, valvular insufficiency, or congenital defects in heart structure.
- **left ventricular failure** – blood backs up into the lungs causing pulmonary edema
  - shortness of breath or sense of suffocation
- **right ventricular failure** – blood backs up in the vena cava causing systemic or generalized edema
  - enlargement of the liver, ascites (pooling of fluid in abdominal cavity), distension of jugular veins, swelling of the fingers, ankles, and feet
- eventually leads to total heart failure

Cardiac Output (CO)

- **cardiac output** (CO) – the amount ejected by ventricle in 1 minute

- **cardiac output = heart rate x stroke volume**
  - about **4 to 6 L/min at rest**
  - a RBC leaving the left ventricle will arrive back at the left ventricle in about 1 minute
  - vigorous exercise increases CO to 21 L/min for fit person and up to 35 L/min for world class athlete

- **cardiac reserve** – the difference between a person's maximum and resting CO
  - increases with fitness, decreases with disease

- to keep cardiac output constant as we increase in age, the heart rate increases as the stroke volume decreases

Heart Rate

- **pulse** – surge of pressure produced by each heart beat that can be felt by palpating a superficial artery with the fingertips
  - infants have HR of 120 bpm or more
  - young adult females avg. 72 - 80 bpm
  - young adult males avg. 64 to 72 bpm
  - heart rate rises again in the elderly
- **tachycardia** - resting adult heart rate above 100 bpm
  - stress, anxiety, drugs, heart disease, or fever
  - loss of blood or damage to myocardium
- **bradycardia** - resting adult heart rate of less than 60 bpm
  - in sleep, low body temperature, and endurance trained athletes
- **positive chronotropic agents** – factors that raise the heart rate
- **negative chronotropic agents** – factors that lower heart rate

Chronotropic Effects of the Autonomic Nervous System

- autonomic nervous system does not initiate the heartbeat, it modulates rhythm and force
- **cardiac centers** in the **reticular formation of the medulla oblongata** initiate autonomic output to the heart
- **cardiostimulatory effect** – some neurons of the cardiac center transmit signals to the heart by way of **sympathetic** pathways
- **cardioinhibitory effect** – others transmit **parasympathetic** signals by way of the **vagus nerve**

Chronotropic Effects of the Autonomic Nervous System

- **sympathetic** postganglionic fibers are adrenergic
  - they release **norepinephrine**
  - binds to **β-adrenergic fibers** in the heart
  - activates **c-AMP second-messenger system** in cardiocytes and nodal cells
  - leads to **opening of Ca^{2+} channels** in plasma membrane
  - increased Ca^{2+} inflow **accelerated depolarization of SA node**
  - **cAMP accelerates the uptake of Ca^{2+} by the sarcoplasmic reticulum** allowing the cardiocytes to **relax more quickly**
  - by accelerating both contraction and relaxation, norepinephrine and cAMP increase the heart rate as high as 230 bpm
  - diastole becomes too brief for adequate filling
  - both stroke volume and cardiac output are reduced

Chronotropic Effects of the Autonomic Nervous System

- **parasympathetic vagus nerves** have cholinergic, inhibitory effects on the SA and AV nodes
  - **acetylcholine (ACh)** binds to **muscarinic receptors**
  - **opens K^+ gates** in the nodal cells
  - as K^+ leaves the cells, they become **hyperpolarized** and fire less frequently
  - **heart slows down**
  - parasympathetics work on the heart faster than sympathetics
    - parasympathetics do not need a second messenger system
- without influence from the cardiac centers, the heart has **a intrinsic "natural" firing rate of 100 bpm**
- **vagal tone** – holds down this heart rate to 70 – 80 bpm at rest
  - steady background firing rate of the **vagus nerves**

Inputs to Cardiac Center

- **cardiac centers in the medulla** receive input from many sources and integrate it into the 'decision' to speed or slow the heart
- **higher brain centers** affect heart rate
  - **cerebral cortex**, **limbic system**, **hypothalamus**
    - sensory or emotional stimuli
- medulla also receives input from muscles, joints, arteries, and brainstem
  - **proprioceptors** in the muscles and joints
    - inform cardiac center about changes in activity, HR increases before metabolic demands of muscle arise
  - **baroreceptors** signal cardiac center
    - pressure sensors in **aorta and internal carotid arteries**
    - blood pressure decreases, signal rate drops, cardiac center increases heart rate
    - if blood pressure increases, signal rate rises, cardiac center decreases heart rate

Inputs to Cardiac Center

- **chemoreceptors**
  - in aortic arch, carotid arteries and medulla oblongata
  - sensitive to blood pH, CO_2 and O_2 levels
  - more important in respiratory control than cardiac control
    - if CO_2 accumulates in blood or CSF (hypercapnia), reacts with water and causes increase in H^+ levels
    - H^+ lowers the pH of the blood possibly creating acidosis (pH < 7.35)
  - hypercapnia and acidosis stimulate the cardiac center to increase heart rate
  - also respond to hypoxemia – oxygen deficiency in the blood
    - usually slows down the heart

- chemoreflexes and baroreflexes, responses to fluctuation in blood chemistry, are both negative feedback loops

Chronotropic Chemicals

- chemicals affect heart rate as well as neurotransmitters from cardiac nerves
  - blood born adrenal catecholamines (NE and epinephrine) are potent cardiac stimulants

- **drugs** that stimulate heart
  - **nicotine** stimulates catecholamine secretion
  - **thyroid hormone** increases number adrenergic receptors on heart so more responsive to sympathetic stimulation
  - **caffeine** inhibits cAMP breakdown prolonging adrenergic effect

Chronotropic Chemicals

- electrolytes
  - K^+ has greatest chronotropic effect
    - **hyperkalemia** – excess K^+ in cardiocytes
      - myocardium less excitable, heart rate slows and becomes irregular
    - **hypokalemia** – deficiency K^+ in cardiocytes
      - cells hyperpolarized, require increased stimulation
  - calcium
    - **hypercalcemia** – excess of Ca^{2+}
      - decreases heart rate and contraction strength
    - **hypocalcemia** – deficiency of Ca^{2+}
      - increases heart rate and contraction strength

Stroke Volume (SV)

- the other factor that in cardiac output, besides heart rate, is **stroke volume**

- three variables govern stroke volume:
  1. preload
  2. contractility
  3. afterload

- example
  - increased preload or contractility causes increases stroke volume
  - increased afterload causes decrease stroke volume

Preload

- **preload** – the amount of tension in ventricular myocardium immediately before it begins to contract
  - increased preload causes increased force of contraction
  - exercise increases venous return and stretches myocardium
  - cardiocytes generate more tension during contraction
  - increased cardiac output matches increased venous return
- **Frank-Starling law of heart** - SV$\propto$ EDV
  - stroke volume is proportional to the end diastolic volume
  - ventricles eject as much blood as they receive
  - the more they are stretched, the harder they contract

Contractility

- **contractility** refers to how hard the myocardium contracts for a given preload

- **positive inotropic agents** increase contractility
  - **hypercalcemia** can cause strong, prolonged contractions and even cardiac arrest in systole
  - **catecholamines** increase calcium levels
  - **glucagon** stimulates cAMP production
  - **digitalis** raises intracellular calcium levels and contraction strength

- negative inotropic agents reduce contractility
  - **hypocalcemia** can cause weak, irregular heartbeat and cardiac arrest in diastole
  - **hyperkalemia** reduces strength of myocardial action potentials and the release of Ca^{2+} into the sarcoplasm
  - **vagus nerves** have effect on atria but too few nerves to ventricles for a significant effect

Afterload

- **afterload** – the blood pressure in the aorta and pulmonary trunk immediately distal to the semilunar valves
  - opposes the opening of these valves
  - limits stroke volume
- **hypertension** increases afterload and opposes ventricular ejection
- anything that impedes arterial circulation can also increase afterload
  - lung diseases that restrict pulmonary circulation
  - **cor pulmonale** – right ventricular failure due to obstructed pulmonary circulation
    - in emphysema, chronic bronchitis, and black lung disease

Exercise and Cardiac Output

- exercise makes the heart work harder and increases cardiac output
- **proprioceptors** signal cardiac center
  - at beginning of exercise, signals from joints and muscles reach the cardiac center of brain
  - sympathetic output from cardiac center increases cardiac output
- increased muscular activity increases venous return
  - increases preload and ultimately cardiac output
- increase in heart rate and stroke volume cause an increase in cardiac output
- exercise produces ventricular hypertrophy
  - increased stroke volume allows heart to beat more slowly at rest
  - athletes with increased cardiac reserve can tolerate more exertion than a sedentary person