The Heart – Ch. 20

*pulmonary circuit*: carries blood to & from gas exchange surfaces of lungs

*systemic circuit*: transports blood to & from rest of body

*each circuit begins & ends at heart; blood travels through these circuits in sequence

*arteries*: efferent vessels; carry blood away from blood

*veins*: afferent vessels; return blood to heart

*capillaries*: small, thin-walled vessels between smallest arteries & veins

*exchange vessels*: capillaries’ thin walls permit exchange of nutrients, dissolved gases, & waste products between blood & surrounding tissues

*heart contains 4 muscular chambers, 2 associated with each circuit

*right atrium*: receives blood from systemic circuit & passes it to right ventricle: discharges blood into pulmonary circuit

*left atrium*: collects blood from pulmonary circuit & empties it into left ventricle: ejects blood through contractions into systemic system

*Anatomy of the Heart

*located near anterior chest wall, directly posterior to sternum

*lies slightly to left of midline; sits at angle to longitudinal axis of body; rotated toward left side

*pericardial cavity*: surrounds heart; located in interior portion of mediastinum

*mediastinum separates 2 pleural cavities; contains thymus, esophagus, & trachea

*space between opposing parietal & visceral surfaces

*normally contains 10-20ml of pericardial fluid: secreted by pericardial membranes; acts as lubricant, reducing friction between opposing surfaces as heart beats

*pericardium*: serous membrane lining pericardial cavity

*subdivided into:

*visceral pericardium: epicardium*: covers outer surface of heart

*parietal pericardium*: lines inner surface of pericardial sac: surrounds heart; reinforced by dense network of collagen fibers; stabilizes position of heart & associated vessels within mediastinum

*superficial anatomy of heart

*2 atria have relatively thin muscular walls & are highly expandable

*when not filled with blood, outer portion of each atria deflates & becomes lumpy, wrinkled flap → auricle

*coronary sulcus*: deep groove that marks border between atria & ventricles

*anterior & posterior interventricular sulcus*: shallower depressions that mark boundary line between left & right ventricles

*base*: superior end of heart where great veins & arteries of circulatory system are connected

*apex*: inferior, pointed tip of heart

*internal anatomy & organization

*2 atria are separated by interatrial septum; 2 ventricles separated by interventricular septum

*each septum is muscular partition

*atrioventricular (AV) valves*: folds of fibrous tissue that extend into openings between atria & ventricles; permit blood flow in one direction only: from atria to ventricles

*right atrium

*receives blood from systemic circuit through 2 great veins:

*superior vena cava*: delivers blood to right atrium from head, neck, upper limbs, & chest

*opens into posterior & superior portion of right atrium


*inferior vena cava*: carries blood to right atrium from rest of trunk, viscera, & lower limbs
*opens into posterior & inferior portion of right atrium
*coronary veins* of heart return blood to *coronary sinus*: opens into right atrium inferior to connection with inferior vena cava
*pectinate muscles*: musculi pectinati; prominent muscular ridges that run along inner surface of auricle & across adjacent anterior atrial wall
*foramen ovale*: oval opening that, during 5th week of embryonic development until birth, penetrates interatrial septum & connects 2 atria
*permits blood flow from right atrium to left atrium while lungs are developing
*fossa ovalis*: small depression where foramen ovale has closed after birth

**right ventricle**
*blood flows from right atrium into right ventricle through broad opening by three fibrous flaps called *cups*: part of right atrioventricular (AV) valve: also known as tricuspid valve
*free edge of each cusp is attached to tendinous connective tissue fibers called chordae tendineae: which originate at papillary muscles: conical muscle projections that arise from inner surface of right ventricle
*valve closes when right ventricle contracts, preventing backflow of blood into right atrium
*internal surface also contains series of muscular ridges called trabeculae carneae
*moderator band: muscular ridge that extends horizontally from inferior portion of interventricular septum & connects to anterior papillary muscle
*contains portion of *conducting system*, an internal network that coordinates contractions of cardiac muscle cells
*delivers contraction stimulus to papillary muscles
*superior end tapers to conical pouch called conus arteriosas: which ends at pulmonary semilunar valve: consists of three semilunar cusps of thick connective tissue
*pulmonary blood passes through this valve to enter pulmonary trunk: start of pulmonary circuit
*once within pulmonary trunk, blood flows into left pulmonary arteries & right pulmonary arteries

**left atrium**
*posterior wall of left atrium receives blood from 2 left & 2 right pulmonary veins* which receive blood from respiratory capillaries
*left atrioventricular (AV) valve, or bicuspid valve*: contains pair of cusps
*also called mitral valve
*permits flow of blood from left atrium into left ventricle

**left ventricle**
*right & left ventricles contain equal amounts of blood, but left ventricles is much larger because it has thicker walls → which enable left ventricle to develop pressure sufficient to push blood through large systemic circuit
*prominent trabeculae carneae & pair of large papillary muscles tense chordae tendineae that brace cusps of AV valve & prevent backflow of blood into atrium
*blood leaves left ventricle by passing through aortic semilunar valve into ascending aorta
*aortic sinuses*: saclike dilations of base of ascending aorta that occur adjacent to each cusp
*prevent individual cusps from sticking to wall of aorta when valve opens
*from ascending aorta, blood flows on through aortic arch & into descending aorta
*pulmonary trunk is attached to aortic arch by ligamentum arteriosum, which marks path of important fetal blood vessel that linked pulmonary & systemic circuits
*structural differences between left & right ventricles*
*right ventricle doesn’t normally need to push very hard to propel blood through pulmonary circuit → lungs are close to heart, & pulmonary vessels are relatively short & wide*
*wall of right ventricle is relatively thin; when it contracts, right ventricle squeezes blood against massive left ventricle → which moves blood very efficiently with minimal effort, but develops relatively low pressures*
*in left ventricle, 6 or 7 times as much force must be exerted to push blood around systemic circuit → so it has extremely thick muscular wall*
*when left ventricle contracts (1) distance between base & apex decreases, & (2) diameter of ventricular chamber decreases*
*as it contracts, it also bulges into right ventricular cavity, which improves efficiency of right ventricle’s efforts*

*heart valves*

*atrioventricular (AV) valves*
*prevent backflow of blood from ventricles to atria when ventricles are contracting*
*during period known as ventricular diastole, ventricles are relaxed*
*as each relaxed ventricle fills with blood, chordae tendineae are loose & AV valves offer no resistance to flow of blood from atria to ventricles*
*ventricles contract during period of ventricular systole*
*as ventricles begin to contract, blood moving back toward atria swings cusps together closing valves*
*at same time, contraction of papillary muscles tenses chordae tendineae & stops cusps before they swing into atria & cause regurgitation, or backflow*

*semilunar valves*
*pulmonary & semilunar valves prevent backflow of blood from pulmonary trunk & aorta into right & left ventricles*
*semilunar valves do not require muscular braces (chordae tendineae) because arterial walls do not contract, & relative positions of cusps are stable*
*when these valves close, 3 symmetrical cusps support one another*

*heart wall*

*epicardium*: visceral pericardium that covers outer surface of heart
*serous membrane that consists of exposed mesothelium & underlying layer of loose connective tissue that is attached to myocardium*

*myocardium*: muscular wall of heart that forms both of atria & ventricles
*contains cardiac muscle tissue, blood vessels, & nerves*
*consists of concentric layers of cardiac muscle tissue*
*atrial myocardium contains muscle bundles that wrap around atria & form figure-eights that pass through interatrial septum*
*superficial ventricular muscle layers spiral around both ventricles; deeper muscle layers spiral around & between ventricles toward apex*

*endocardium*: covers inner surfaces of heart, including heart valves
*simple squamous epithelium that is continuous with endothelium of attached blood vessels*

*cardiac muscle tissue*
*cardiac muscle cells interconnected by intercalated discs: convey force of contraction cell to cell & propagate action potentials*
*cardiac muscle is relatively short, highly branched, & has normally only one centrally-located nucleus*
*has many mitochondria → higher mitochondrial presence, the greater capillary density*
**connective tissue & fibrous skeleton**
- Connective tissues of heart include large numbers of collagen & elastic fibers
- Each cardiac muscle is wrapped in strong but elastic sheath, & adjacent cells are tied together by fibrous cross-links or "struts"
- These fibers are in turn interwoven into sheets that separate superficial & deep muscle layers
- Connective tissue fibers:
  - Provide physical support for cardiac muscle fibers, blood vessels, & nerves of myocardium
  - Help distribute forces of contraction
  - Add strength & prevent over-expansion of heart
  - Provide elasticity that helps return heart to its original size & shape after contraction

**fibrous skeleton** of heart consists of 4 dense bands of fibroelastic tissue that encircle bases of pulmonary trunk, aorta, & heart valves
- Bands stabilize positions of heart valves & ventricular muscle cells & physically isolate ventricular cells from atrial cells

**blood supply to heart**
- **Coronary circulation**: supplies blood to muscles of heart
  - **Coronary arteries**: originate at base of ascending aorta – blood pressure here is highest in systemic circuit & this pressure ensures continuous flow of blood to meet demands of active cardiac muscle tissue
    - **Right coronary artery**: follows coronary sulcus around heart; supplies blood to:
      - Right atrium
      - Portions of both ventricles
      - Portions of conducting system of heart, including sinoatrial (SA) valves & AV nodes
      - Cells of SA & AV node are essential to establishing normal heart rate
      - Inferior to right atrium; gives rise to one or more marginal branches: extend across ventricular surface
      - Continues across posterior surface of heart, supplying posterior interventricular branch, or posterior descending artery, which runs toward apex within posterior interventricular sulcus & supplies blood to interventricular septum & adjacent portions of ventricles
    - **Left coronary artery**: supplies blood to left ventricles, left atrium, & interventricular septum
      - Gives rise to:
        - Circumflex branch: curves to left around coronary sulcus, eventually meeting & fusing with small branches of right coronary artery
        - Anterior interventricular branch: much larger; left anterior descending artery
          - Swings around pulmonary trunk & runs along anterior surface within anterior interventricular sulcus
          - Supplies small tributaries, anatomizes continuous with those of posterior interventricular branch of right coronary artery
  - **Cardiac veins**
    - **Great cardiac vein**: begins on anterior surface of ventricles, along interventricular sulcus
      - Drains blood from region supplied by anterior interventricular branch of left coronary artery
      - Reaches level of atria & then curves around left side of heart within coronary sulcus
      - Vein empties into coronary sinus: large, thin-walled vein that lies in posterior portion of coronary sulcus
*coronary sinus communicates with right atrium near base of inferior vena cava
*other cardiac veins, which empty into great cardiac vein or coronary sinus include:
  * **posterior cardiac vein**: draining area served by circumflex branch of left coronary artery
  * **middle cardiac vein**: draining area supplied by posterior interventricular branch of right coronary artery
  * **small cardiac vein & anterior veins**: draining other regions supplied by right coronary artery & its tributaries

*innervation of heart
*sympathetic & parasympathetic divisions of ANS provide innervation to heart through **cardiac plexus**
*postganglionic sympathetic neurons are located in cervical & upper thoracic ganglia
*vagus nerve (N X) carries parasympathetic preganglionic fibers to small ganglia in cardiac plexus
*both ANS divisions innervate SA & AV nodes & atrial muscle cells
* **cardiac centers** of medulla oblongata contain autonomic headquarters for cardiac control
  * stimulation of cardioacceleratory center activates necessary sympathetic neurons
  * **cardioinhibitory center**: governs activities of parasympathetic neurons
*cardiac centers receive input from higher centers especially from parasympathetic & sympathetic headquarters in hypothalamus
*monitor baroreceptors & chemoreceptors innervated by glossopharyngeal (N IX) & vagus nerves (N X)
  * on basis of this info, they adjust cardiac performance to maintain adequate circulation to vital organs, such as brain
*centers respond to changes in blood pressure & in arterial concentrations of dissolved oxygen & carbon dioxide

*The Heartbeat*
*in single heartbeat, entire heart contracts in coordinated manner so that blood flows in right direction at proper time
*two types of cardiac muscle are involved in normal heartbeat:*
* **contractile cells**: produce powerful contractions that propel blood
  * form bulk of atrial & ventricular walls – account for roughly 99% of muscle cells in heart
  * in both cardiac muscle cells & skeleton muscle fibers (1) action potential leads to appearance of Ca$^{2+}$ among myofibrils, & (2) binding of Ca to troponin on thin filaments initiates contraction
* **action potential in cardiac muscle cells**
  * begins when membrane of ventricular muscle cell is brought to threshold; normally occurs in portion of membrane next to intercalated disc
  * typical stimulus is excitation of adjacent muscle cell
  * once threshold has been reached, action potential proceeds in three basic steps:
  * **rapid depolarization**
    * at threshold, voltage-regulated Na channels (fast channels) open & membrane suddenly becomes permeable to Na$^+$ → result is rapid depolarization of sarcolemma
  * **the plateau**
    * as sodium channels are closing, voltage-regulated Ca$^{2+}$ channels (slow channels) are opening
*presence of plateau is major difference between action potentials in cardiac muscle cells & skeletal muscle fibers

*repolarization
  *as plateau continues, slow Ca\(^{2+}\) channels begin closing & slow potassium channels begin opening → result is period of rapid repolarization that restores resting potential

*refractory period: period of time after action potential begins that membrane will not respond normally to second stimulus
  *absolute refractory period: membrane cannot respond at all because Na\(^+\) channels are either already open or closed & inactivated
  *relative refractory period: follows absolute refractory period; voltage-regulated Na\(^+\) channels are closed but capable of opening
  *membrane will respond to stronger-than-normal stimulus by initiating another action potential

*Ca\(^{2+}\) ions & cardiac contractions
  *appearance of action potential in cardiac muscle cell membrane produces contraction by causing increase in concentration of Ca\(^{2+}\) around myofibrils; occurs in two steps:
    *Ca\(^{2+}\) ions entering cell membrane during plateau phase of action potential provide roughly 20% of Ca\(^{2+}\) required for contraction
    *arrival of extracellular Ca\(^{2+}\) is trigger for release of additional Ca\(^{2+}\) from reserves in sarcoplasmic reticulum (SR)
  *extracellular Ca\(^{2+}\) ions thus have direct & indirect effects on cardiac muscle cell contraction
  *in skeletal muscle fibers, action potential is relatively brief & ends as related twitch contraction begins
    *twitch contraction is short & ends as SR reclaims Ca\(^{2+}\) it released
  *in cardiac muscle sell, action potential is prolonged & Ca ions continue to enter cell throughout plateau → as result, period of active muscle cell contraction continues until plateau ends
    *as slow Ca\(^{2+}\) channels close, intracellular Ca\(^{2+}\) ions are absorbed by SR or pumped out & muscle cell relaxes
  *in skeletal muscle fibers, refractory period ends before muscle fiber develops peak tension → twitches can summate & tetanus can occur
  *in cardiac muscle cells, absolute refractory period continues until relaxation is under way
    *because summation is not possible, tetanic contraction cannot occur in normal cardiac muscle cell → “A heart in tetany could not pump blood”

*conducting system: is network of specialized muscle cells that initiates & distributes electrical impulses & controls & coordinates activities of contractile cells
  *cardiac muscle contracts on its own (unlike skeletal muscle) in absence of neural or hormonal stimulation – automaticity or autorhythmicity
  *system includes:
    *sinoatrial node: located in wall of right atrium
    *atrioventricular (AV) node: located at junction between atria & ventricles
    *conducting cells: interconnect two nodes & distribute contractile stimulus throughout myocardium
    *those in atria are found in internodal pathways, which distribute contractile stimulus to atrial muscle cells as impulse travels from SA node to AV node ventricular conducting cells include those in AV bundle & bundle braches as well as Purkinje fibers, which distribute stimulus to ventricular myocardium
*cells of conducting system are smaller than contractile cells of myocardium, contain very few myofibrils, & they cannot maintain stable resting potential
*each time repolarization occurs, membrane again gradually drifts toward threshold → prepotential
*rate of spontaneous depolarization is fastest at SA node, which in absence of neural or hormonal stimulation will generate action potential at rate of 80-100 per minute
*isolated nodes of AV node depolarize more slowly
*under normal conditions, most cells of AV bundle, bundle branches, & Purkinje fibers do not depolarize spontaneously
*SA node reaches threshold first → establishes heart rate

**sinoatrial (SA) node**: embedded in posterior wall of right atrium, near entrance of superior vena cava
*contains pacemaker cells: establish heart rate
*connected to larger AV node by internodal pathways in atrial walls

**atrioventricular (AV) node**: sits within floor of right atrium near opening of coronary sinus
*rate of propagation slows as impulse leaves internodal pathways & enters AV node
*delay at AV node – atria must contract before ventricles; once ventricles start contracting, AV valves close
*if all chambers contracted at same time AV valves would prevent blood flow from atria & into ventricles
*atrial myocardium completes its contraction before ventricular contraction begins due to delay
*cells of AV node can conduct impulses at maximum rate of 230 per minute → maximum normal heart rate

**AV bundle, bundle branches, & Purkinje fibers**
*connection between AV node & AV bundle, bundle of His, is only electrical connection between atria & ventricles
*once impulse enters AV bundle, it travels to interventricular septum & enters right & left bundle branches (left-supplies relatively massive left ventricle
*as branches diverge, they conduct impulses to Purkinje fibers & papillary muscles
*Purkinje fibers conduct action potentials very rapidly, about 75 msec
*within above time, signal to begin contraction has reached all ventricular cardiac muscle cells
*because bundle braches deliver impulse across moderator band to papillary muscles directly rather than via Purkinje fibers, papillary muscles begin contracting before rest of ventricular musculature
*this contraction applies tension to chordae tendineae, bracing AV valves
*by limiting movement of cusps, tension in papillary muscles prevents backflow of blood into atria when ventricles contract
*ventricular contraction proceeds in wave that begins at apex & spreads towards base
*ectopic pacemaker: activity partially or completely bypasses conducting system, disrupting timing of ventricular contraction → result is dangerous reduction in efficiency of heart

**electrocardiogram (ECG or EKG)**: recording of electrical activities occurring in heart that are powerful enough to be detected by electrodes on body surface
*electrical activity of heart is directly related to performance of specific nodal, conducting & contractile components
*will reveal abnormal pattern of impulse conduction
**P waves** – small waves that accompany depolarization of atria
QRS complex: appears as ventricles depolarize
relatively strong electrical signal, because mass of ventricular muscle is much larger than that of atria
ventricles begin contracting shortly after peak of R wave
T wave: smaller wave that indicates ventricular repolarization
Cardiac cycle: period between start of one heartbeat & beginning of next
includes alternating periods of contraction & relaxation
Systole: contraction; chamber contracts & pushes blood into adjacent chamber or into arterial trunk; pressure within chamber rises
Diastole: relaxation; follows systole; chamber fills with blood & prepares for next cardiac cycle; pressure within chamber falls
blood will flow from one chamber to another only if pressure in first chamber exceeds pressure in second
basic principle governs movement of blood between atria & ventricles, between ventricles & arterial trunks, & between major veins & atria
correct pressure relationships are dependent on careful timing of contractions
atrial systole & ventricular systole do NOT occur at same time; same for diastole
cycle is determined by atria & it includes one cycle of atrial systole & atrial diastole
Phases of cycle:
as cycle begins, chambers are relaxed & ventricles are partially filled with blood
during atrial systole, atria contract & ventricles become completely filled with blood
atria next enter period of atrial diastole, which continues until start of next cardiac cycle
as atrial diastole begins, ventricular systole occurs where blood is pushed through systemic & pulmonary circuits toward atria
heart then enters period of ventricular diastole
for rest of this cycle, filling occurs passively & both atria & ventricles are relaxed
Pressure & volume changes in cardiac cycle
both sides of heart contract at same time & eject same amount of blood, though pressure in right atrium & ventricle are lower
Atrial systole
as atria contract, rising atrial pressures push blood into ventricles through open right & left AV valves
at start, ventricles are already filled to about 70% of capacity
at end, each ventricle contains end-diastolic volume (EDV): maximum amount of blood that it will hold in cycle, about 130ml for adult standing at rest, typically
Ventricular systole
as pressures inside ventricles rise above those in atria, AV valves swing shut
during this stage, ventricles are contracting – blood flow has yet to occur, because ventricular pressures are not high enough to force open semilunar valves & push blood into pulmonary or aortic trunks
ventricles contract isometrically; generate tension & ventricular pressures rise
ventricle now in period of isovolumetric contraction: all heart valves are closed, volume of ventricle remains constant, & ventricular pressure rises
once pressure in ventricle exceeds that in arterial trunk, semilunar valves open & blood flows into pulmonary & aortic trunks – marks beginning of period of ventricular ejection
ventricles now contract isotonically; muscle cells shorten, & tension production remains relatively constant
after reaching peak, ventricular pressures gradually decline near end
*stroke volume (SV):* percentage of end-diastolic volume of ventricle; also known as *ejection fraction* – can vary in response to changing demands on heart; most important factor in examination of single cardiac cycle

*at end, ventricular pressures fall rapidly
*blood in aorta & pulmonary trunks now starts to flow back toward ventricles, & this movement closes semilunar valves
*as backflow begins, pressure decreases in aorta; when semilunar valves close, pressure rises again as elastic arterial walls recoil
*this small, temporary rise produces valley in pressure tracing known as *dicrotic notch*
*end-systolic volume (ESV):* amount of blood remaining in ventricle when semilunar valve closes

*ventricular diastole
*all heart valves are now closed & ventricular myocardium is relaxing
*isovolumetric relaxation: period where blood cannot flow into ventricles because ventricular pressure is still higher that atrial pressure
*ventricular pressures decline rapidly over this period because elasticity of connective tissues of heart & fibrous skeleton helps reexpand ventricles toward their resting dimensions
*when ventricular pressures fall below those of atria, atrial pressure forces AV valves open – blood now flows from atria to ventricles
*pressures in ventricles are so far below those in major veins that blood pours through relaxed atria & into ventricles
*heart failure: condition where one or both ventricles are damaged which can leave heart unable to maintain adequate blood flow through peripheral tissues & organs

*heart sounds
*austrulation: technique of listening to heart by using stethoscope
*four sounds designated S₁ – S₄
*S₁ – known as “lubb” lasts longer than S₂; marks start of ventricular contraction; produced as AV valve close
*S₂ – known as “dubb” occurs as beginning of ventricular filling, when semilunar valves close
*S₁ & S₂ more prominent – easily heard
*S₃ & S₄ – usually very faint & seldom heard in healthy adults
*associated with blood flowing into ventricles (S) & atrial contraction (S) rather than valve action

*energy for cardiac contractions
*when heart is beating, energy required is obtained by mitochondrial breakdown of fatty acids (stored as lipid droplets) & glucose (stored as glycogen)
in addition to obtaining oxygen from coronary circulation, cardiac muscle cells maintain sizable reserves of oxygen bound to heme units of myoglobin molecules

*Cardiodynamics
*movements & forces generated during cardiac contractions
*cardiac output: amount of blood pumped by each ventricle in one minute
*provides useful indication of ventricular efficiency over time
*CO = stroke volume (SV) x heart rate (HR)
*precisely adjusted so that peripheral tissues receive adequate circulatory supply under variety of conditions
**cardiac reserve**: difference between resting & maximal cardiac output

**factors controlling stroke volume**

*SV* is difference between end-diastolic volume (EDV) & end-systolic volume (ESV)

**EDV**

*affected by 2 factors:

*filling time*: duration of ventricular diastole

*depends entirely on heart rate → faster heart rate, shorter available filling time*

*venous return*: rate of blood flow over this period

*changes in response to alterations in cardiac output, blood volume, patterns of peripheral circulation, skeletal muscle activity, etc*

*greater EDV, greater SV*

**ESV**

*influenced by 3 factors:

*preload*: degree of stretching experienced during ventricular diastole

*directly proportional to EDV; greater EDV, larger preload*

*significant because it affects ability of muscle cells to produce tension*

*amount depends on demands placed on heart*

*Frank-Starling Principle*: Starling’s law of the Heart; relationship between amount of ventricular stretching & contractile force means that within normal physiological limits, increasing EDV results in corresponding increase in SV

*most obvious effect of principle is that outputs of left & right ventricles remain balanced under variety of conditions*

*contractility*: amount of forced produced during contraction, at given preload

*under normal circumstances, it may be altered by autonomic innervation or circulating hormone*

*factors that increase contractility are said to have positive inotropic action; these typically stimulate Ca\(^{2+}\) entry into cardiac muscle cells, thus increasing force & duration*

*factors that decrease contractility are said to have negative inotropic action; these may block Ca\(^{2+}\) movement or depress cardiac muscle metabolism in some way*

*autonomic activity* – alters degree of contraction & changes ESV in following ways:

*sympathetic stimulation has positive inotropic effect – it causes release of norepinephrine (NE) by postganglionic fibers & secretion of epinephrine (E) & NE by adrenal medulla*

*stimulate cardiac muscle cell metabolism & increase force & degree of contraction*

*net effect is that ventricles contract more forcefully, increasing ejection fraction & decreasing ESV*

*parasympathetic stimulation from vagus nerve has negative inotropic effect*

*primary effect of acetylcholine (Ach) is at membrane surface, where it produces hyperpolarization & inhibition*

*primary result is decrease in heart rate through effects on SA & AV nodes*

*also reduction in force of cardiac contractions*

*hormones*

*E & NE have positive inotropic effects*

*glucagon has positive inotropic effect – used more before synthetic inotropic agents were available*

*thyroid hormones have positive inotropic effects*
*changes in ion concentration
*changes in extracellular Ca\(^{2+}\) concentrations affect primarily strength & duration of cardiac contractions
*hypercalcemia: condition where extracellular concentrations of Ca\(^{2+}\) are elevated
*cardiac muscle cells become extremely excitable & their contractions become prolonged & powerful
*hypocalcemia: condition where extracellular concentrations of Ca\(^{2+}\) are abnormally low
*contractions become very weak & may cease altogether
*changes in extracellular K\(^+\) concentration affect primarily transmembrane potential & rates of depolarization & repolarization
*hyperkalemia: condition where K\(^+\) concentrations are high
*muscle cells depolarize & repolarization is inhibited; cardiac contractions then become weak & irregular, & in severe cases heart eventually stops in diastole
*hypokalemia: condition where K\(^+\) concentrations are abnormally low
*membranes of cardiac muscle cells hyperpolarize, & their rate of contraction declines
*heart rate decreases & blood pressure falls; in severe cases heart eventually stops in systole
*afterload: amount of tension contracting ventricle must produce to force open semilunar valve & eject blood
*as afterload increases, stroke volume decreases
*increased by any factor that restricts blood flow through arterial system
*if afterload is too great, ventricle will be unable to eject blood
*autonomic activity & circulating hormones are responsible for making delicate adjustments to heart rate as circulatory demands change
*significant changes in ion concentration or body temperature are unusual & may indicate problems with homeostatic control mechanisms
*all these factors act by modifying natural rhythm of heart
*bradycardia: term used to indicate heart rate that is slower than normal
*tachycardia: indicates faster-than-normal heart rate
*autonomic innervation
*heart has resting autonomic tone
*both autonomic divisions are normally active at steady background level, releasing ACh & NE both at nodes & into myocardium
*in healthy, resting individual, parasympathetic effects dominate
*heart rate in absence of autonomic innervation is established by pacemaker cells of SA node
*if parasympathetic activity increases, heart rate declines further
*autonomic innervation affects heart rate
*sympathetic & parasympathetic division alter heart rate by changing permeabilities of cells in conducting system
*most dramatic effects are at SA node, where there are changes in rate of impulse generation that affect heart rate
*autonomy effect also increases & decreases rate of impulse propagation along conducting system
*any factor that changes rate of spontaneous depolarization or duration of repolarization will alter heart rate by changing time required to reach threshold
*Acetylcholine released by parasympathetic neurons opens chemically regulated K\(^+\) channels in cell membrane
  *This opening dramatically slows rate of spontaneous depolarization & also slightly extends duration of repolarization → result is decline in heart rate
*NE released by sympathetic neurons binds to beta-1 receptors; this binding leads to opening of Ca\(^{2+}\) ion channels
  *Influx of Ca increases rate of depolarization & shortens period of repolarization
  *Nodal cells reach threshold more quickly, & heart rate increases

*atrial reflex
  *Bainbridge reflex; involves adjustments of heart rate in response to increase in venous return
  *When walls of right atrium are stretched, stimulation of stretch receptors in atrial walls trigger reflexive increase in heart rate caused by increased sympathetic activity

*hormones
  *Epinephrine, norepinephrine, & thyroid hormone increase contractility & cause increase in heart rate
  *Effects of E on SA node are similar to those of NE
  *E also affects contractile cells; after massive sympathetic stimulation of adrenal medullae, myocardium may become so excitable that abnormal contractions occur

*Changes in ion concentration
  *Rate SA node establishes depends on:
    *Resting membrane potential of nodal cells
    *Rate of spontaneous depolarization
  *Changes in extracellular K\(^+\) concentrations will alter resting potential at SA node & thereby change heart rate
    *When extracellular concentrations of K\(^+\) decline, rate of K\(^+\) diffusion out of nodal cell increases
    *As result decrease in extracellular K\(^+\) ion concentration leads to membrane hyperpolarization & reduction of heart rate
  *Changes in concentration affect SA node & conducting system, but these effects are overshadowed by effects of contractility of myocardium

*Changes in body temperature
  *Temperature changes affect metabolic operations throughout body
    *Reduction of temp slows rate of depolarization at SA node, lowers heart rate, & reduces strength of cardiac contractions
    *Elevated body temp elevates heart rate & contractile force
  *Cardiac output & heart rate
    *Cardiac output cannot increase indefinitely, primarily because available filling time becomes shorter & shorter as heart rate increases

*Heart & Cardiovascular System
  *Goal of cardiovascular regulation is to maintain adequate blood flow to all body tissues
  *When blood pressure changes, cardiovascular centers not only adjust heart rate but also alter diameters of peripheral blood vessels