Basics & Beyond: Conduction System A&P, Myocardial Stimulation, and Pacing Basics

Chris Benson, MS, CCDS

BIOTRONIK excellence for life

1

Anatomy & Physiology of the Cardiac Conduction System

BIOTRONIK excellence for life

2

Objectives
Cardiac Conduction System Anatomy & Physiology

- List the structures that comprise the cardiac conduction system
- Identify gross anatomical location of the components of the cardiac conduction system and other structures
- List the physiologic function and qualities of the sinoatrial node, atrioventricular node, bundle of His and the bundle branches
- List the steps of normal conduction and how it correlates with the surface ECG

BIOTRONIK
excellence for life

3

Cardiac Conduction System A & P
What is the Cardiac Conduction System?

What is it?	Specialized tissue involved in the generation and conduction of electrical impulses throughout the heart.
Why is it important?	Foundational knowledge of the cardiac conduction system is essential to understanding appropriate device therapy
What are the main components of the Cardiac Conduction System?	Sinoatrial (SA) node Atrioventricular (AV) node His-purkinje system

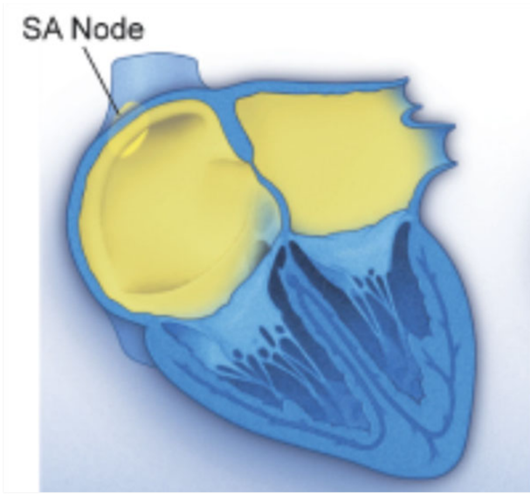
Bunch TJ, Hayes DL, Swerdlow CD, Asirvatham SJ, Friedman PA. Pacing and Defibrillation: Clinically Relevant Basics for Practice. Published online December 17, 2012:1-39. doi:https://doi.org/10.1002/9781118483923.ch1

4

BIOTRONIK
excellence for life

4

Cardiac Conduction System Anatomy & Physiology
Sinoatrial Node



The Sinoatrial (SA) Node
- Located at the **junction of the right atrium (RA) and superior vena cava (SVC)**
- Dense collagen matrix of large, centrally located **P cells** surrounded by **transitional cells** and fiber tracts
- Innervated by the **autonomic nervous system (ANS)** and responds to sympathetic/parasympathetic tone
- **Highest rate of spontaneous depolarization**
- Specialized fibers such as **Bachmann's bundle** conduct the impulse throughout the right and left atria.

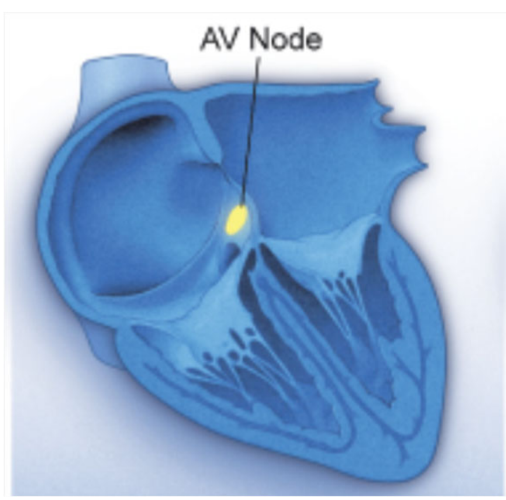
Bunch TJ, Hayes DL, Swerdlow CD, Asirvatham SJ, Friedman PA. Pacing and Defibrillation: Clinically Relevant Basics for Practice. Published online December 17, 2012:1-39. doi:https://doi.org/10.1002/9781118483923.ch1

5

BIOTRONIK excellence for life

5

Cardiac Conduction System Anatomy & Physiology
Atrioventricular Node



The Atrioventricular (AV) Node
- Small, **subendocardial** structure located within the **interatrial septum**
- Loose collagen matrix of **P cells** and **transitional cells**, and occasionally **purkinje cells** and **myocardial contractile fibers**
- Innervated by the **ANS**
- Allows for physiologic delay between atrial and ventricular contraction
- Functions as a **subsidiary "pacemaker"** if the SA node fails
- **Regulates the number of impulses** that reach the ventricle

Bunch TJ, Hayes DL, Swerdlow CD, Asirvatham SJ, Friedman PA. Pacing and Defibrillation: Clinically Relevant Basics for Practice. Published online December 17, 2012:1-39. doi:https://doi.org/10.1002/9781118483923.ch1

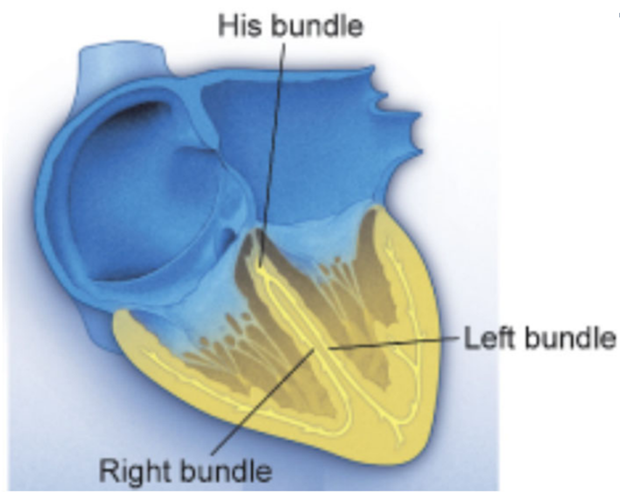
6

BIOTRONIK excellence for life

6

Cardiac Conduction System Anatomy & Physiology

His-Purkinje System



The His-Purkinje System

- Purkinje fibers emerge from the distal AV node to form the **bundle of His**
- The bundle of His runs through the **membranous septum** to the **crest of the muscular septum** before dividing into **right** and **left bundle branches**
- The **right bundle** runs along the right side of the **interventricular septum**, dividing at the **anterior papillary muscle**
- The **left bundle branches** and divides into **anterior**, **septal**, and **posterior fascicles**
- Both terminate in individual **purkinje fibers** interdigitating with myocardial contractile fibers

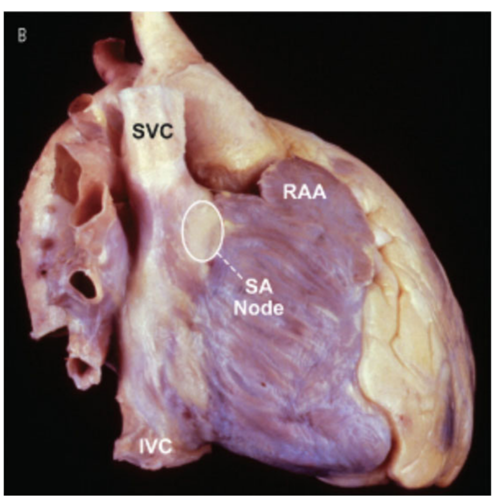
Bunch TJ, Hayes DL, Swerdlow CD, Asirvatham SJ, Friedman PA. Pacing and Defibrillation: Clinically Relevant Basics for Practice. Published online December 17, 2012:1-39. doi:https://doi.org/10.1002/9781118483923.ch1

7 BIOTRONIK excellence for life

7

Cardiac Conduction System Anatomy & Physiology

Gross Anatomy: Part I



Gross Anatomy: Part I

- External View of the heart
- **Sinoatrial (SA) Node** located in the epicardium at the junction of the superior vena cava and right atrium
- **Superior vena cava (SVC)**
- **Inferior vena cava (IVC)**
- **Right atrial appendage (RAA)**

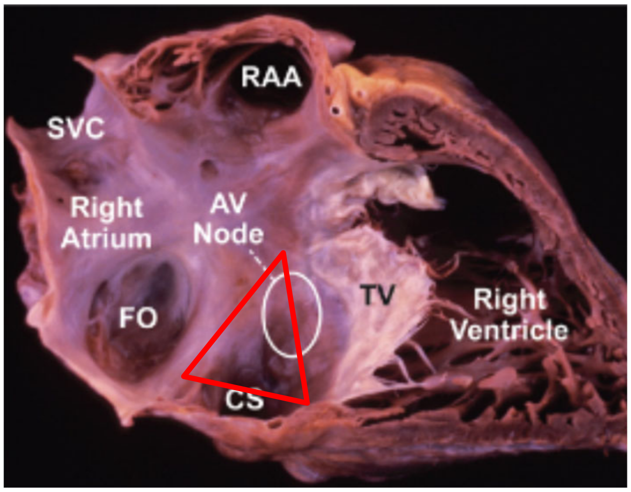
Bunch TJ, Hayes DL, Swerdlow CD, Asirvatham SJ, Friedman PA. Pacing and Defibrillation: Clinically Relevant Basics for Practice. Published online December 17, 2012:1-39. doi:https://doi.org/10.1002/9781118483923.ch1

8 BIOTRONIK excellence for life

8

Cardiac Conduction System Anatomy & Physiology

Gross Anatomy: Part II



Gross Anatomy: Part II

- External View of the heart with the right atrial and ventricular free wall removed
- The **atrioventricular (AV) node** is situated in the **triangle of Koch**, an anatomical triangle bounded by the **tricuspid valve (TV)**, **coronary sinus (CS)**, and **tendon of Todaro**
- Fossa ovalis (FO)
- Superior vena cava (SVC)
- Right atrial appendage (RAA)

Bunch TJ, Hayes DL, Swerdlow CD, Asirvatham SJ, Friedman PA. Pacing and Defibrillation: Clinically Relevant Basics for Practice. Published online December 17, 2012:1-39. doi:https://doi.org/10.1002/9781118483923.ch1

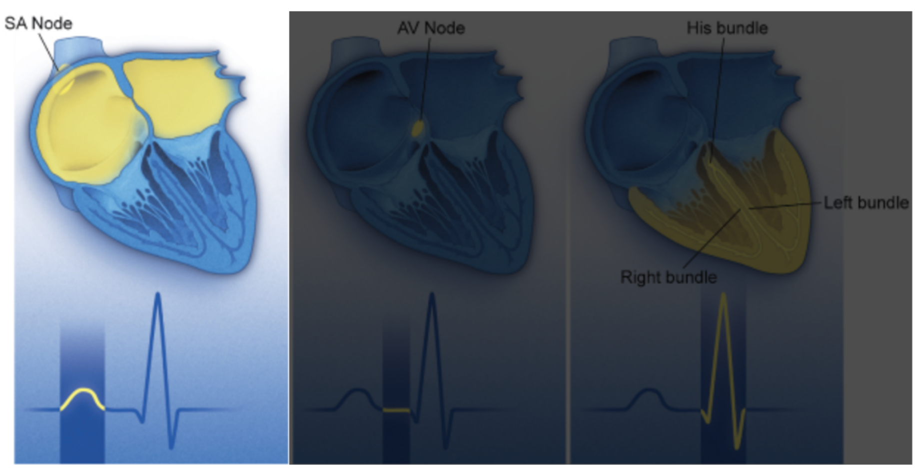
9

BIOTRONIK excellence for life

9

Cardiac Conduction System Anatomy & Physiology

Normal Conduction



Part I

- Conduction begins with impulse generation in the **sinoatrial (SA) node**.
- Specialized fibers such as **Bachmann's bundle** conduct the impulse through R and L atria
- Propagation of the impulse gives rise to the **P wave** on surface ECG

Bunch TJ, Hayes DL, Swerdlow CD, Asirvatham SJ, Friedman PA. Pacing and Defibrillation: Clinically Relevant Basics for Practice. Published online December 17, 2012:1-39. doi:https://doi.org/10.1002/9781118483923.ch1

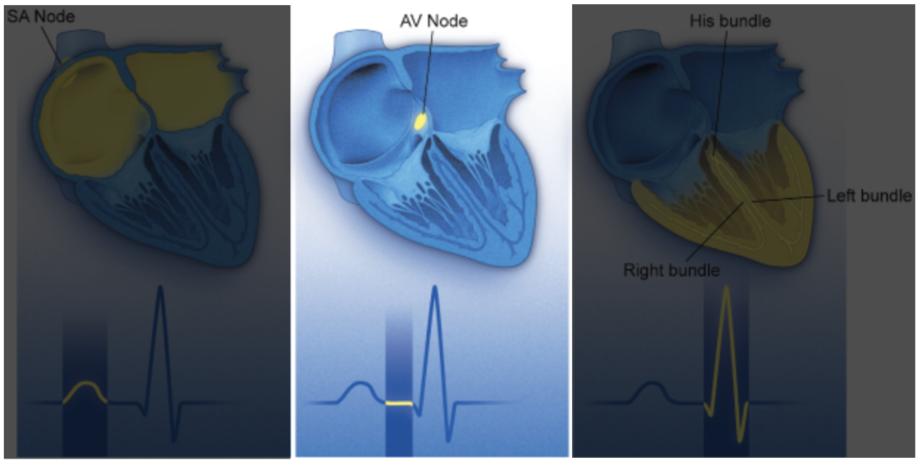
10

BIOTRONIK excellence for life

10

Cardiac Conduction System Anatomy & Physiology

Normal Conduction



Part II

- The electrical impulse from the atria converges on the **atrioventricular (AV) node**.
- The AV node provides a **physiologic delay** between atrial and ventricular contractions for **optimal hemodynamic function**
- The **PR interval** is represented by impulse propagation through the **AV node and His-purkinje fibers**

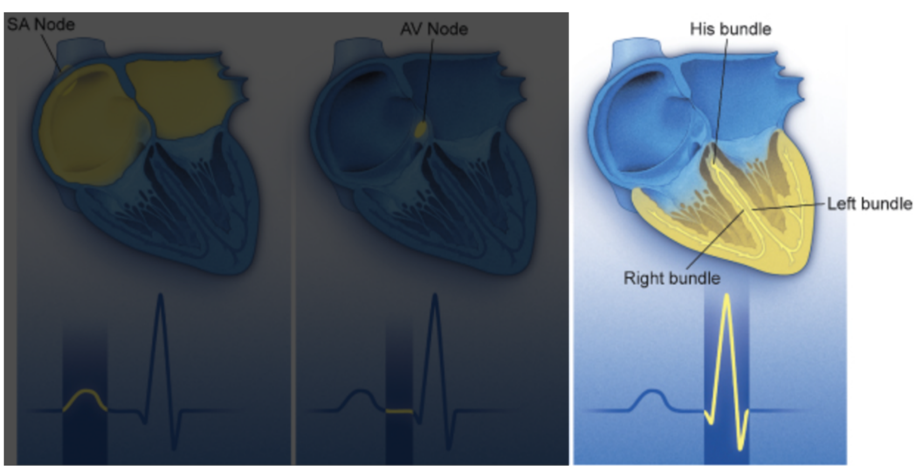
Bunch TJ, Hayes DL, Swerdlow CD, Asirvatham SJ, Friedman PA. Pacing and Defibrillation: Clinically Relevant Basics for Practice. Published online December 17, 2012:1-39. doi:https://doi.org/10.1002/9781118483923.ch1

BIOTRONIK excellence for life

11

Cardiac Conduction System Anatomy & Physiology

Normal Conduction



Part III

- The wavefront passes through the His-purkinje system to rapidly activate ventricular myocardium
- **Ventricular contraction** gives rise to the large amplitude **QRS complex**.

Bunch TJ, Hayes DL, Swerdlow CD, Asirvatham SJ, Friedman PA. Pacing and Defibrillation: Clinically Relevant Basics for Practice. Published online December 17, 2012:1-39. doi:https://doi.org/10.1002/9781118483923.ch1

BIOTRONIK excellence for life

12

Electrophysiology of Myocardial Stimulation

13

Objectives

Electrophysiology of Myocardial Stimulation

- Describe the process of myocardial stimulation
- Define the role of the transmembrane potential and ion channels in myocardial excitation
- Describe the phases of a purkinje fiber action potential
- Describe how the wavefront moves from cell to cell

14

Electrophysiology of Myocardial Stimulation
How does it work?

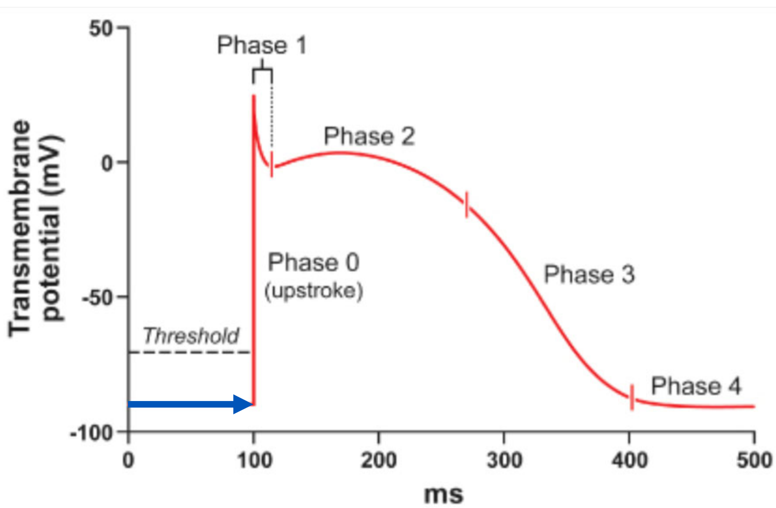
The elements of myocardial excitation:

- Maintenance of a highly negative membrane potential (-90mV)
- Initiation of a wave of depolarization by a native "pacemaker" or artificial stimulus
- "Excitability" of cardiac myocytes – a disproportionate response to the stimulus
- Rapid influx of positive sodium ions across the cellular membrane during depolarization
- Active transport of ions during repolarization to return to the negative membrane potential necessary for excitation
- Propagation of the wave of depolarization to neighboring cells via "gap junctions"

Bunch TJ, Hayes DL, Swerdlow CD, Asirvatham SJ, Friedman PA. Pacing and Defibrillation: Clinically Relevant Basics for Practice. Published online December 17, 2012:1-39. doi:https://doi.org/10.1002/9781118483923.ch1

BIOTRONIK
excellence for life

Electrophysiology of Myocardial Stimulation
Purkinje Fiber Action Potential



Resting Membrane Potential

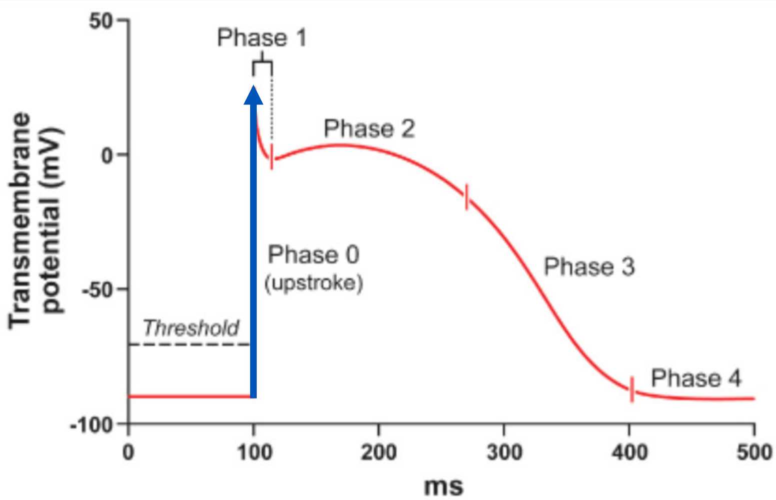
- The transmembrane potential of -90mV is created by maintenance of high concentrations of extracellular sodium (Na+) ions and intracellular potassium (K+) ions
- Passive leakage of ions occurs and is offset by active transport of 3Na+ out of and 2K+ into the cell, which maintains polarization.

Bunch TJ, Hayes DL, Swerdlow CD, Asirvatham SJ, Friedman PA. Pacing and Defibrillation: Clinically Relevant Basics for Practice. Published online December 17, 2012:1-39. doi:https://doi.org/10.1002/9781118483923.ch1
Sperelakis N. Chapter 19 - Electrogenesis of Membrane Excitability. ScienceDirect. Published January 1, 2012. https://www.sciencedirect.com/science/article/pii/B9780123877383000196

BIOTRONIK
excellence for life

Electrophysiology of Myocardial Stimulation

Purkinje Fiber Action Potential



Phase 0 - Depolarization

- Eventually the -90mV membrane potential approaches the threshold potential of **-70 to -60mV**
- Fast Na+ ion channels undergo conformation changes to an active state and allow **rapid influx of extracellular Na+** into the myocyte
- The transmembrane potential approaches **20mV**

Bunch TJ, Hayes DL, Swerdlow CD, Asirvatham SJ, Friedman PA. Pacing and Defibrillation: Clinically Relevant Basics for Practice. Published online December 17, 2012:1-39. doi:https://doi.org/10.1002/9781118483923.ch1
Sperelakis N. Chapter 19 - Electrogenesis of Membrane Excitability. ScienceDirect. Published January 1, 2012. https://www.sciencedirect.com/science/article/pii/B9780123877383000196

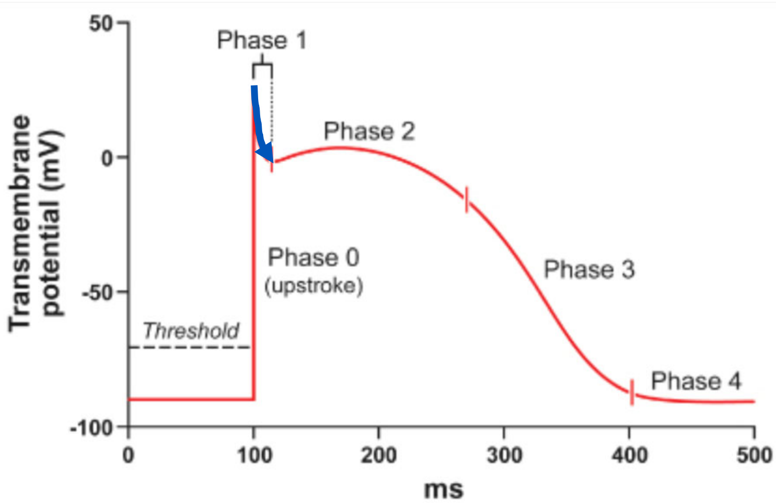
17

BIOTRONIK excellence for life

17

Electrophysiology of Myocardial Stimulation

Purkinje Fiber Action Potential



Phase 1 - Early Repolarization

- The rapid influx of Na+ ions in Phase 0 triggers a brief period of overshoot potential
- Potassium (K+) channels open and K+ efflux returns the transmembrane potential to 0mV

Bunch TJ, Hayes DL, Swerdlow CD, Asirvatham SJ, Friedman PA. Pacing and Defibrillation: Clinically Relevant Basics for Practice. Published online December 17, 2012:1-39. doi:https://doi.org/10.1002/9781118483923.ch1
Sperelakis N. Chapter 19 - Electrogenesis of Membrane Excitability. ScienceDirect. Published January 1, 2012. https://www.sciencedirect.com/science/article/pii/B9780123877383000196

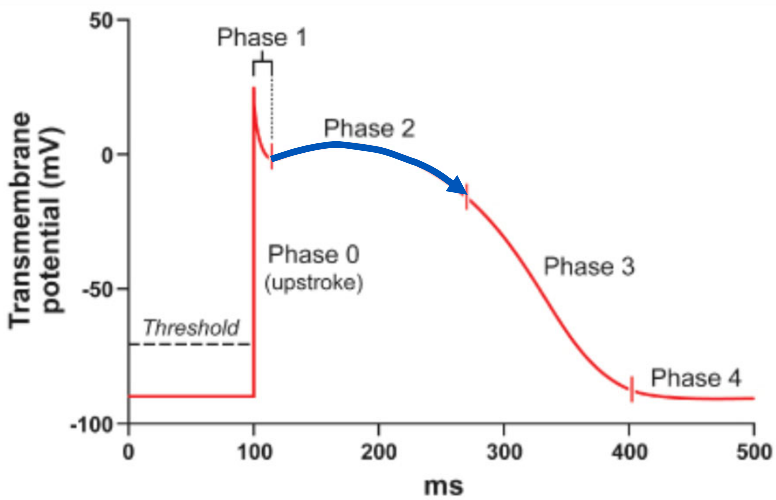
18

BIOTRONIK excellence for life

18

Electrophysiology of Myocardial Stimulation

Purkinje Fiber Action Potential



Phase 2 – Plateau Period

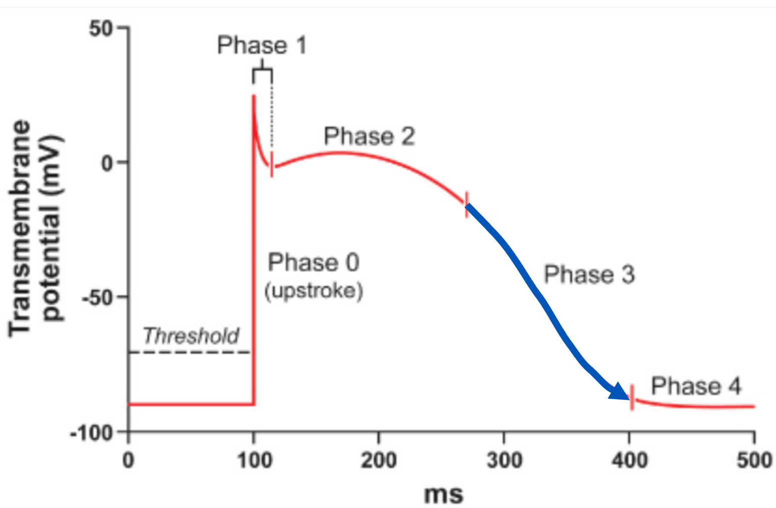
- During Phase 2 (the Plateau period), influx of calcium (Ca2+) and sodium (Na+) ions is offset by efflux of potassium (K+) ions.
- The transmembrane potential remains relatively constant during Phase 2

Bunch TJ, Hayes DL, Swerdlow CD, Asirvatham SJ, Friedman PA. Pacing and Defibrillation: Clinically Relevant Basics for Practice. Published online December 17, 2012:1-39. doi:https://doi.org/10.1002/9781118483923.ch1
Sperelakis N. Chapter 19 - Electrogenesis of Membrane Excitability. ScienceDirect. Published January 1, 2012. https://www.sciencedirect.com/science/article/pii/B9780123877383000196

BIOTRONIK excellence for life

Electrophysiology of Myocardial Stimulation

Purkinje Fiber Action Potential



Phase 3 – Repolarization / Relative Refractory Period (RRP)

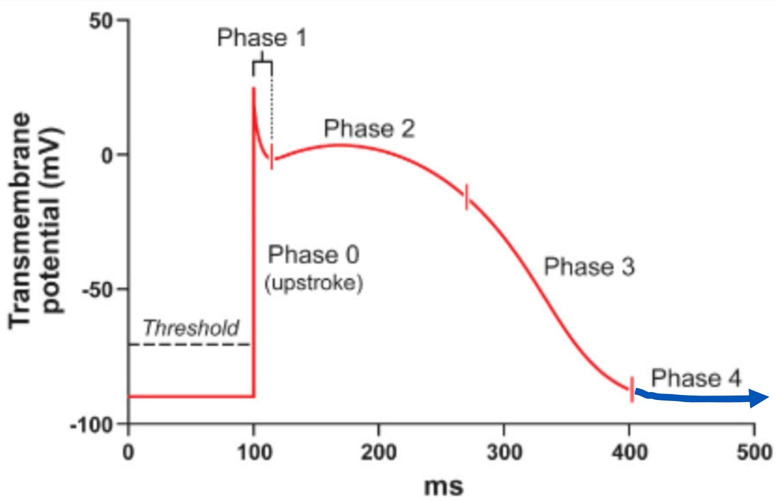
- In Phase 3, calcium (Ca2+) ion channels close, but potassium (K+) channels remain open, allowing continued efflux of K+ ions.
- The transmembrane potential returns to -90mV
- A greater than normal stimulus is required to trigger depolarization

Bunch TJ, Hayes DL, Swerdlow CD, Asirvatham SJ, Friedman PA. Pacing and Defibrillation: Clinically Relevant Basics for Practice. Published online December 17, 2012:1-39. doi:https://doi.org/10.1002/9781118483923.ch1
Sperelakis N. Chapter 19 - Electrogenesis of Membrane Excitability. ScienceDirect. Published January 1, 2012. https://www.sciencedirect.com/science/article/pii/B9780123877383000196

BIOTRONIK excellence for life

Electrophysiology of Myocardial Stimulation

Purkinje Fiber Action Potential



Phase 4 – Resting Membrane Potential

- In Phase 4, active transport of sodium (Na+) ions out of the cell and potassium (K+) ions into the cell restores the balance of intracellular K+ ions.
- Gradually, the transmembrane potential begins to drift upward towards the threshold potential of -70 to -60mV, allowing for depolarization to repeat

Bunch TJ, Hayes DL, Swerdlow CD, Asirvatham SJ, Friedman PA. Pacing and Defibrillation: Clinically Relevant Basics for Practice. Published online December 17, 2012:1-39. doi:https://doi.org/10.1002/9781118483923.ch1
Sperelakis N. Chapter 19 - Electrogenesis of Membrane Excitability. ScienceDirect. Published January 1, 2012. https://www.sciencedirect.com/science/article/pii/B9780123877383000196

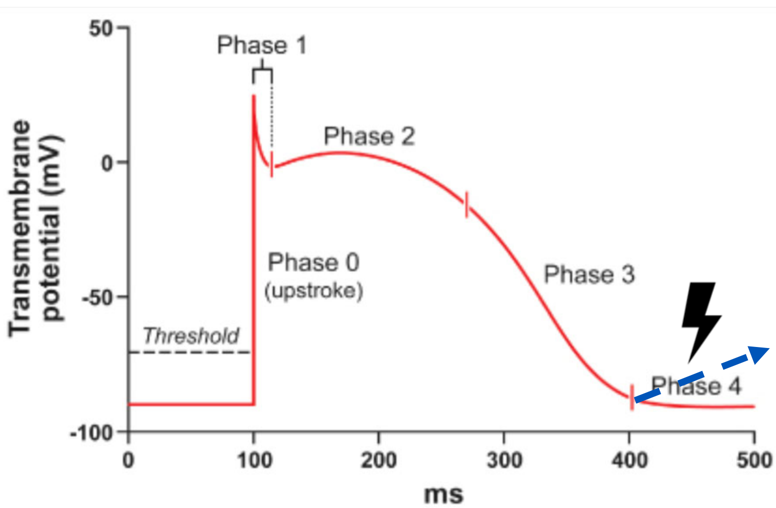
21

BIOTRONIK excellence for life

21

Electrophysiology of Myocardial Stimulation

Purkinje Fiber Action Potential



Depolarization Wavefront

- Depolarization of neighboring cells occurs via gap junctions that allow positive ions to flow from one depolarizing cell to the next
- These connections allow rapid conduction of the action potential through the heart tissue
- Pacemaker stimulus of a sufficient output can also lead to depolarization

Bunch TJ, Hayes DL, Swerdlow CD, Asirvatham SJ, Friedman PA. Pacing and Defibrillation: Clinically Relevant Basics for Practice. Published online December 17, 2012:1-39. doi:https://doi.org/10.1002/9781118483923.ch1
Sperelakis N. Chapter 19 - Electrogenesis of Membrane Excitability. ScienceDirect. Published January 1, 2012. https://www.sciencedirect.com/science/article/pii/B9780123877383000196

22

BIOTRONIK excellence for life

22

Pacing Basics: Stimulation Threshold

BIOTRONIK
excellence for life

23

Objectives

Pacing Basics: Stimulation Threshold

- Describe the components of the stimulus: pulse amplitude and pulse duration
- Describe the strength-duration curve
- Define the *rheobase* and *chronaxie* on the strength-duration curve
- Define Ohm's law and describe the relationship between stimulus energy (E), voltage (V), pacing impedance (R), pulse duration (t), and current (C).
- Describe polarization
- Describe typical variations in stimulation threshold

BIOTRONIK
excellence for life

24

Pacing Basics: Stimulation Threshold
How does it work?

The stimulation threshold and how it relates to pacing:

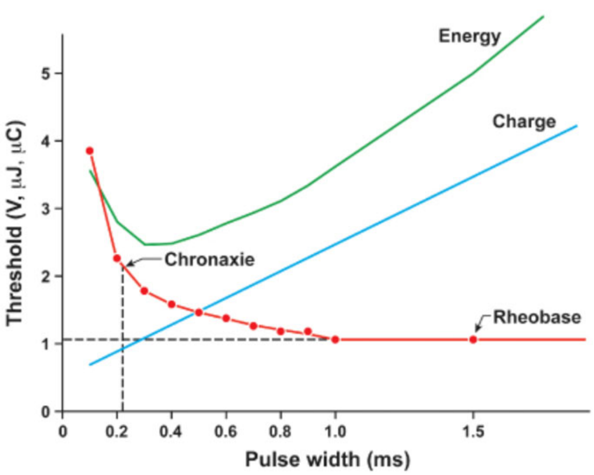
- Pacing the heart involves delivery of an electrical impulse of sufficient strength and duration to the myocardium by an electrode.
- The stimulation threshold is the minimal amount of energy required to cause successful depolarization of the myocardium in contact with the electrode, and propagation of that depolarization to surrounding myocardium.
- The components of the stimulation threshold are pulse amplitude, measured in volts (V), and pulse duration/width, the length of time the impulse is delivered, measured in milliseconds (ms).
- Typically, stimulation threshold is communicated in a format such as: “1.25 V @ 0.4ms”.

Bunch TJ, Hayes DL, Swerdlow CD, Asirvatham SJ, Friedman PA. Pacing and Defibrillation: Clinically Relevant Basics for Practice. Published online December 17, 2012:1-39. doi:https://doi.org/10.1002/9781118483923.ch1

BIOTRONIK excellence for life

25

Pacing Basics: Stimulation Threshold
Strength-Duration Curve



Strength Duration Curve

- An exponential relationship exists between the stimulus pulse amplitude (V) and the stimulus pulse duration/width (ms)
- At very short pulse widths, small changes result in a significant change in the pulse amplitude required to achieve myocardial depolarization.
- At longer pulse widths, small changes have little effect on the stimulus pulse amplitude

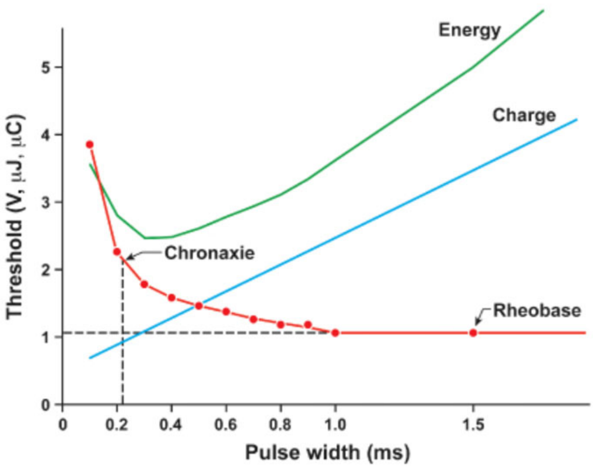
Bunch TJ, Hayes DL, Swerdlow CD, Asirvatham SJ, Friedman PA. Pacing and Defibrillation: Clinically Relevant Basics for Practice. Published online December 17, 2012:1-39. doi:https://doi.org/10.1002/9781118483923.ch1

BIOTRONIK excellence for life

26

Pacing Basics: Stimulation Threshold

Rheobase & Chronaxie



Rheobase and Chronaxie

- 2 important points along the strength-duration curve should be noted.
- The rheobase is the smallest pulse amplitude (Volts) that stimulates the myocardium at an infinitely long pulse duration (milliseconds)
- The chronaxie is the threshold pulse duration at 2x the rheobase voltage and can be helpful in determining an optimal pulse width.
- In this example we can see that the rheobase is 1.1 V, so the rheobase is the pulse duration at 2.2V, which is ~0.2ms

Bunch TJ, Hayes DL, Swerdlow CD, Asirvatham SJ, Friedman PA. Pacing and Defibrillation: Clinically Relevant Basics for Practice. Published online December 17, 2012:1-39. doi:https://doi.org/10.1002/9781118483923.ch1

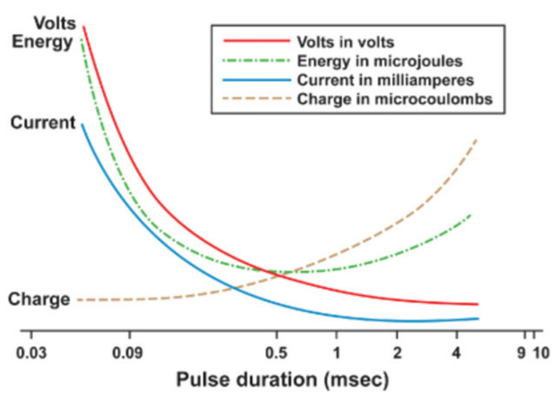
27

BIOTRONIK excellence for life

27

Pacing Basics: Stimulation Threshold

Stimulus Energy, Voltage, Resistance, and Pulse duration



Stimulus Energy Formula

- Voltage (V), pacing impedance/resistance (R), and pulse duration (t) are related to stimulus energy (E) by the following formula:
- $E = V^2 / R \times t$
- Impedance is the resistance to current flow in the pacing system, measured in Ohms
- Stimulus energy is generally lowest between pulse durations of 0.5 – 1.0ms.
- Stimulus energy is generally higher below 0.5ms and above 1.0ms

Bunch TJ, Hayes DL, Swerdlow CD, Asirvatham SJ, Friedman PA. Pacing and Defibrillation: Clinically Relevant Basics for Practice. Published online December 17, 2012:1-39. doi:https://doi.org/10.1002/9781118483923.ch1

28

BIOTRONIK excellence for life

28

Thank You!!!

BIOTRONIK
excellence for life

29

Question 1

Stimulation of the heart by the sympathetic nervous system results in the following:

a) Negative chronotropic effect, negative inotropic effect, negative dromotropic effect
b) Positive chronotropic effect, negative inotropic effect, negative dromotropic effect
c) Positive chronotropic effect, positive inotropic effect, positive dromotropic effect
d) Negative chronotropic effect, positive inotropic effect, negative dromotropic effect

Answer: c

BIOTRONIK
excellence for life

30

Question 1

Stimulation of the heart by the sympathetic nervous system results in the following:

a) Negative chronotropic effect, negative inotropic effect, negative dromotropic effect
b) Positive chronotropic effect, negative inotropic effect, negative dromotropic effect
c) Positive chronotropic effect, positive inotropic effect, positive dromotropic effect
d) Negative chronotropic effect, positive inotropic effect, negative dromotropic effect

- Stimulation of the heart by the sympathetic nervous system results in an increase in heart rate (chronotropy), cardiac contractility (inotropy), and speed of conduction through the AV node (dromotropy).

- Stimulation of the heart by the parasympathetic nervous system results in a decrease in heart rate (chronotropy), cardiac contractility (inotropy), and speed of conduction through the AV node (dromotropy).

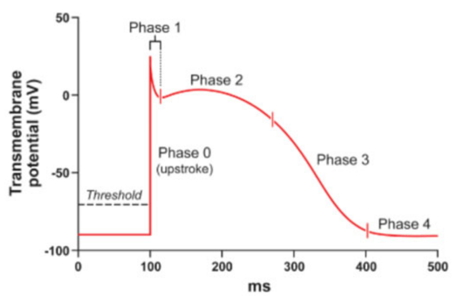
BIOTRONIK
excellence for life

31

Question 2

Which phase of the cardiac action potential correlates to the Relative Refractory Period?

a) Phase 0
b) Phase 1
c) Phase 2
d) Phase 3
e) Phase 4



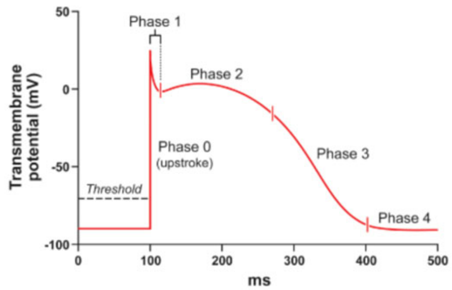
BIOTRONIK
excellence for life

32

Question 2

Which phase of the cardiac action potential correlates to the Relative Refractory Period?

a) Phase 0
b) Phase 1
c) Phase 2
d) Phase 3
e) Phase 4



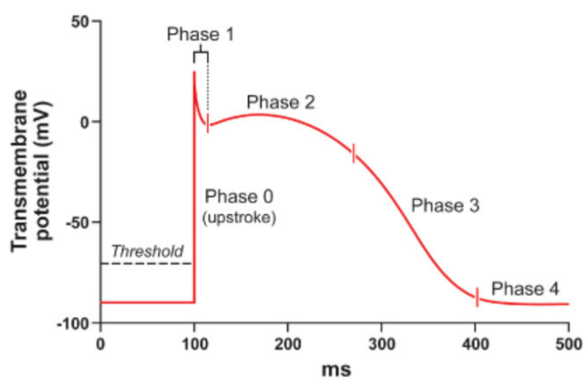
BIOTRONIK
excellence for life

33

Question 3

In which phase(s) of cardiac action potential is the extracellular transmembrane potential more negative than the intracellular potential? (Select all that apply)

a) Phase 0
b) Phase 1
c) Phase 2
d) Phase 3
e) Phase 4



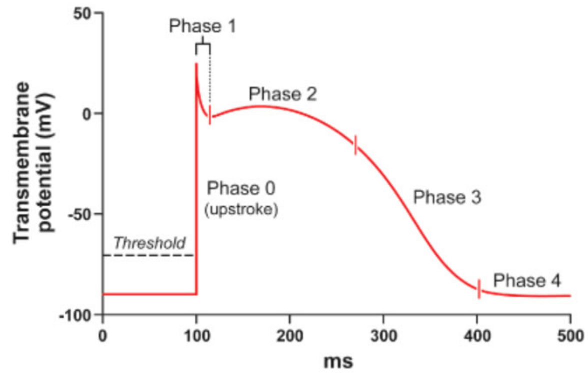
BIOTRONIK
excellence for life

34

Question 3

In which phase(s) of cardiac action potential is the extracellular transmembrane potential more negative than the intracellular potential? (Select all that apply)

a) Phase 0
b) Phase 1
c) Phase 2
d) Phase 3
e) Phase 4



BIOTRONIK
excellence for life

35

Question 4

The smallest pulse amplitude (Volts) that stimulates the myocardium at an infinitely long pulse duration (milliseconds) is the:

a) Stimulus threshold
b) Rheobase
c) Strength-duration curve
d) Chronaxie

BIOTRONIK
excellence for life

36

Question 4

The smallest pulse amplitude (Volts) that stimulates the myocardium at an infinitely long pulse duration (milliseconds) is the:

a) Stimulus threshold
b) Rheobase
c) Strength-duration curve
d) Chronaxie