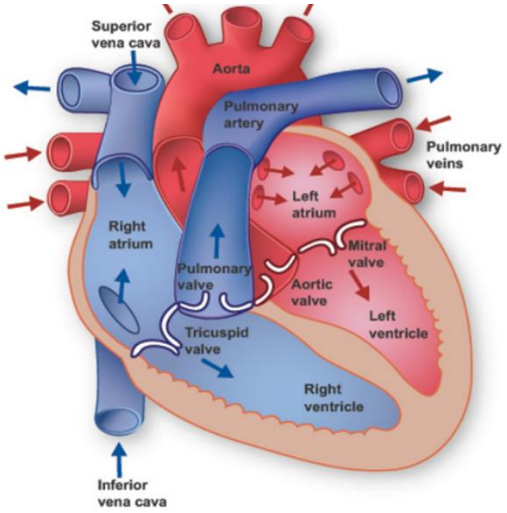
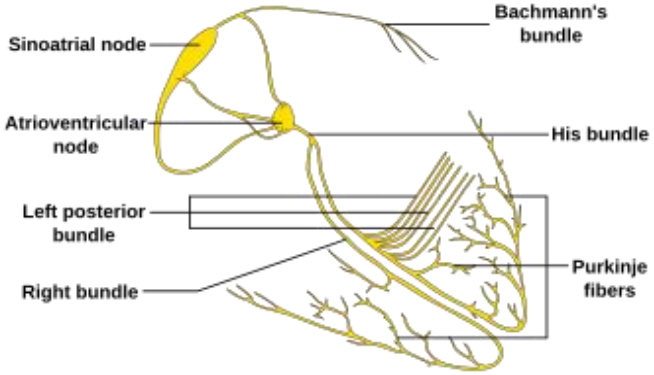
The Physiology of Cardiac Muscle

Introduction

Cardiac muscle is a specialized type of involuntary, striated muscle tissue found exclusively in the heart. It is designed to contract continuously and rhythmically throughout life without fatigue. The unique structural and electrical properties of cardiac muscle enable it to function as an efficient pump that maintains the circulation of blood through both the pulmonary and systemic systems. Unlike skeletal muscle, which requires neural stimulation for each contraction, the cardiac muscle possesses an intrinsic mechanism that generates rhythmic electrical impulses automatically, ensuring a consistent heartbeat independent of external nerve input. However, the activity of the heart is finely modulated by autonomic nerves and circulating hormones .





Structural Characteristics of Cardiac Muscle

The cardiac muscle fiber, or myocyte, shares several features with skeletal muscle but also possesses key differences that allow for its unique function. Each cardiac fiber is short, branched, and interconnected with other fibers, forming a complex network that resembles a three-dimensional lattice. The cells typically contain a single centrally located nucleus, although some cells may be binucleated. Cardiac myocytes contain the same contractile proteins—actin and myosin—as skeletal muscle, arranged in sarcomeres that give the tissue a striated appearance under the microscope.

A defining feature of cardiac muscle is the intercalated disc, a specialized junctional structure located at the ends of adjacent cardiac cells. The intercalated disc consists of three main components: desmosomes, fascia adherens, and gap junctions. Desmosomes and fascia adherens provide strong mechanical connections between cells, ensuring that the force of contraction is transmitted efficiently across the myocardium. Gap junctions, on the other hand, are low-resistance channels that permit the rapid flow of ions between cells, allowing electrical impulses to propagate quickly and uniformly. Through these junctions, the entire myocardium behaves as a functional syncytium—meaning that once one cell is excited, the impulse spreads throughout the tissue so that the heart contracts as a coordinated unit.

The heart is organized into two separate syncytia: the atrial syncytium, which forms the walls of the atria, and the ventricular syncytium, which forms the walls of the ventricles. These two regions are electrically insulated from each other by a fibrous connective tissue layer, with the atrioventricular (AV) node serving as the only normal electrical bridge between them. This separation allows the atria to contract first, ensuring that the ventricles fill with blood before they contract.

Electrical Properties of Cardiac Muscle

Cardiac muscle cells are electrically excitable, and their activity is governed by rapid changes in membrane potential. The resting membrane potential of a typical ventricular contractile cell ranges from –85 to –95 millivolts (mV), primarily due to the high permeability of the membrane to potassium ions (K^+) and the activity of the Na^+/K^+ ATPase pump. In contrast, pacemaker cells of the sinoatrial (SA) and atrioventricular (AV) nodes have a less negative resting potential, around –60 mV, and exhibit spontaneous depolarization due to slow inward sodium and calcium currents.

When a cardiac muscle cell is excited, it undergoes a characteristic action potential that is markedly different from that of skeletal muscle. The cardiac action potential lasts approximately 250 milliseconds, compared with only 2 milliseconds in skeletal muscle. It consists of five distinct phases:

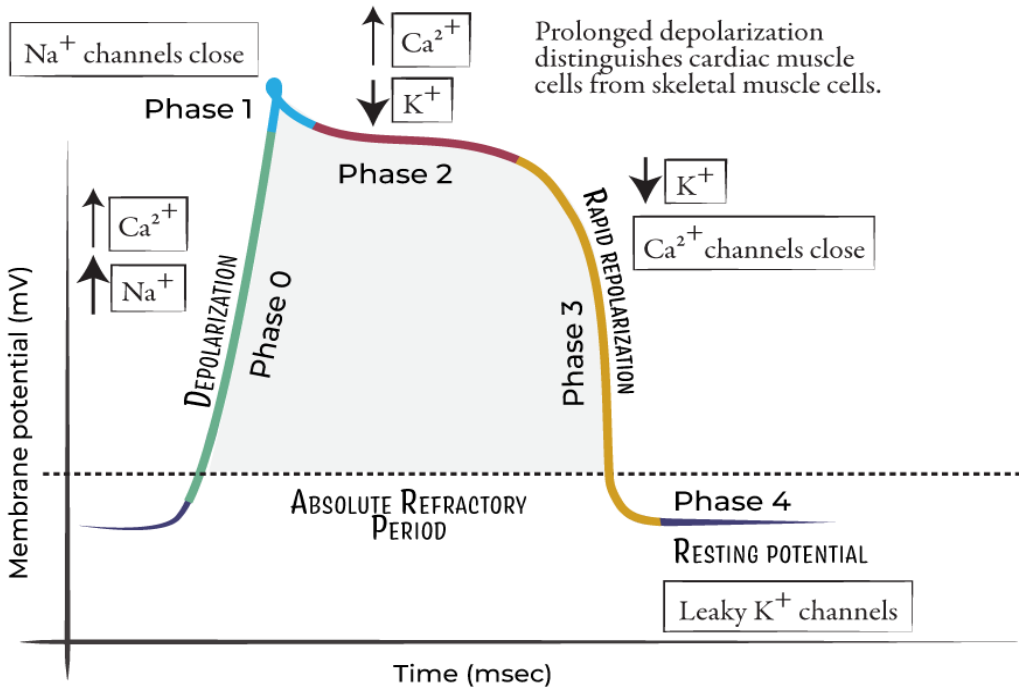
1- Phase 0 (Depolarization): A rapid upstroke occurs as voltage-gated fast sodium channels open, allowing an influx of Na^+ ions.

2- Phase 1 (Initial Repolarization): The sodium channels inactivate, and a brief efflux of K^+ produces a small downward deflection.

3- Phase 2 (Plateau Phase): This is a unique feature of cardiac muscle. The membrane potential remains near 0 mV due to a balance between inward calcium current (through L-type Ca^{2+} channels) and outward K^+ current. The plateau ensures a sustained contraction long enough for complete ejection of blood from the ventricles.

4- Phase 3 (Repolarization): Calcium channels close while more K^+ channels open, allowing K^+ efflux that restores the resting potential.

5- Phase 4 (Resting Phase): The membrane potential returns to its resting level, maintained by the Na^+/K^+ ATPase pump and K^+ leak channels.



The presence of the plateau phase prolongs the refractory period, preventing premature re-excitation of the myocardium. This ensures that each contraction is followed by sufficient relaxation, avoiding tetanic contraction that would be incompatible with effective pumping.

Excitation–Contraction Coupling

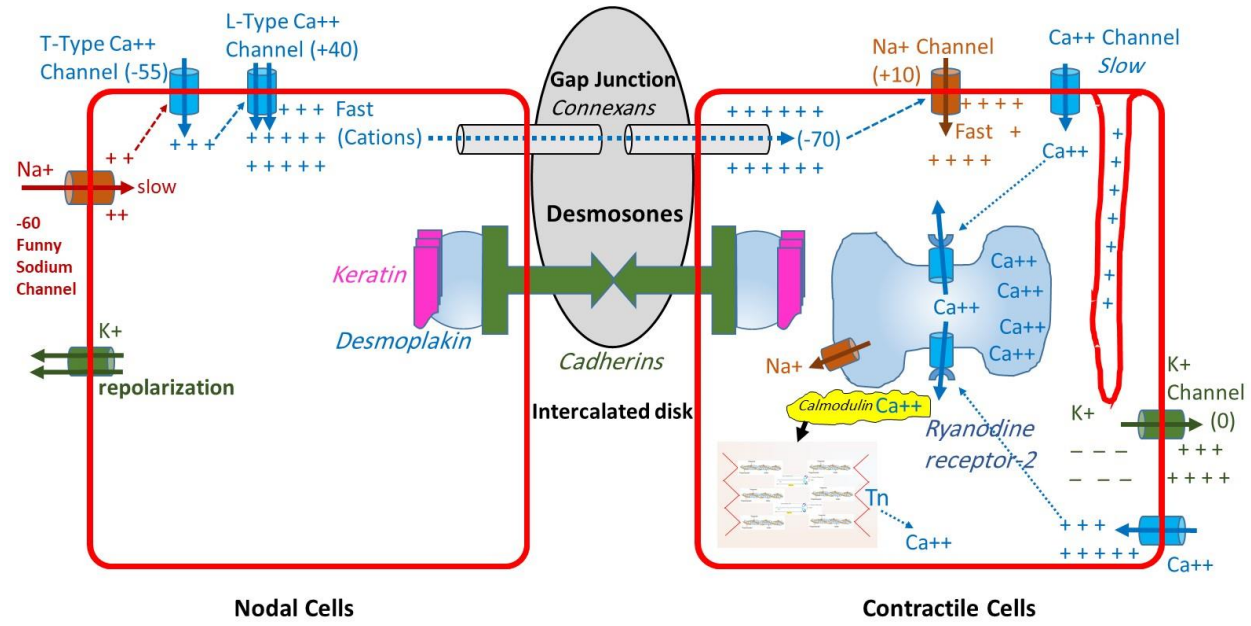
Excitation–contraction coupling in cardiac muscle links the electrical depolarization of the cell membrane with the mechanical process of contraction. When an action potential spreads over the cardiac cell membrane and into the transverse (T) tubules, it activates voltage-gated L-type calcium channels, leading to the entry of a small amount of calcium into the cytosol. This calcium influx, though modest, plays a critical role by triggering a much larger release of calcium from the sarcoplasmic reticulum (SR) through ryanodine receptor channels—a mechanism known as calcium-induced calcium release.

The increased cytosolic calcium binds to troponin C, causing conformational changes that move tropomyosin away from actin's binding sites, thereby allowing the interaction between actin and myosin. The sliding of these filaments generates tension and results in muscle contraction. When the action potential ends, calcium is rapidly removed from the cytoplasm through three main mechanisms: reuptake into the SR by the SERCA pump, extrusion through the Na^{+}/Ca^{2+} exchanger, and to a lesser extent, by a Ca^{2+}-ATPase pump in the sarcolemma. As intracellular calcium concentration decreases, the muscle relaxes. Thus, the strength of cardiac contraction depends directly on the amount of calcium available to the contractile filaments.

Intrinsic (Conducting) System of the Heart

The rhythmic beating of the heart originates from the intrinsic conduction system, a specialized network of modified cardiac muscle fibers that generate and distribute electrical impulses throughout the myocardium. The primary pacemaker is the sinoatrial (SA) node, located in the right atrium near the opening of the superior vena cava. The cells of the SA node possess unstable resting potentials that slowly depolarize due to a gradual inward "funny current" (If) carried by sodium and calcium ions. When the threshold potential is reached, an action potential is

generated, initiating each heartbeat. The SA node normally fires at a rate of 70–80 times per minute in a healthy adult.



Intrinsic Conduction

From the SA node, the impulse spreads rapidly through both atria via internodal pathways and reaches the atrioventricular (AV) node, located in the lower part of the interatrial septum. The AV node serves as the only normal electrical connection between the atria and ventricles and introduces a delay of about 0.1 second. This delay allows time for the atria to contract and complete ventricular filling before the ventricles begin to contract.

After leaving the AV node, the impulse travels through the atrioventricular bundle (Bundle of His), which divides into right and left bundle branches running along the interventricular septum. These branches give rise to a network of Purkinje fibers that spread throughout the ventricular myocardium. Purkinje fibers conduct impulses very rapidly, ensuring that depolarization reaches all parts of the ventricles almost simultaneously, resulting in a coordinated and powerful contraction. The sequence of excitation is thus: SA node → atria → AV node → Bundle of His → bundle branches → Purkinje fibers → ventricular muscle.

Extrinsic (Autonomic) Regulation of Cardiac Activity

Although the heart possesses its own intrinsic rhythm, its activity is finely regulated by the autonomic nervous system (ANS) and circulating hormones to adapt to the body's needs. The sympathetic nervous system increases both heart rate and the force of contraction, while the parasympathetic (vagal) system exerts an opposing, inhibitory influence.

Sympathetic fibers arise from the upper thoracic spinal segments (T1–T5) and reach the heart through the cardiac nerves. The neurotransmitter released is norepinephrine, which acts on β_1-adrenergic receptors in the SA node, AV node, and ventricular muscle. Activation of these receptors increases the rate of depolarization of pacemaker cells, shortens conduction time through the AV node, and enhances calcium influx in contractile cells, thereby increasing the strength of contraction (positive inotropic effect).

Parasympathetic fibers reach the heart via the vagus nerve, originating from the medulla oblongata. The neurotransmitter acetylcholine acts on M_2-muscarinic receptors, opening K^+ channels and causing hyperpolarization of pacemaker cells. This slows the rate of spontaneous depolarization, leading to a decreased heart rate (negative chronotropic effect) and reduced conduction through the AV node. The parasympathetic influence is more pronounced on the atria than on the ventricles because vagal fibers are more concentrated in the atrial regions.

Thus, while the intrinsic conduction system determines the basic rhythm of the heart, the extrinsic autonomic inputs adjust its rate and contractility according to physiological demands such as exercise, stress, or rest.

Control Type	Neurotransmitter / Hormone	Effect on Heart Rate & Conduction	Effect on Nodal Cells	Effect on Contractile Cells
Sympathetic (↑ activity)	Norepinephrine / Epinephrine	↑ Heart rate and faster conduction	Faster depolarization of SA node and AV node	Stronger contraction (↑ Ca^{2+} entry)
Parasympathetic (↑ activity)	Acetylcholine	↓ Heart rate and slower conduction	Slower depolarization of SA node and AV node	Little effect (slight ↓ in atria only)
Adrenal hormones	Epinephrine, Norepinephrine	↑ Heart rate and contractility	↑ SA node firing	↑ Strength of contraction
Thyroid hormone	Thyroxine (T_4)	Slight long-term ↑ in heart rate	↑ Sensitivity of SA node	Mild ↑ in contractility

Refractory Period and Prevention of Tetany

The cardiac muscle exhibits a prolonged refractory period that coincides almost entirely with the duration of the action potential. The absolute refractory period, lasting about 250 milliseconds, prevents the initiation of another action potential while the muscle is still contracting. This feature is essential because it ensures that each contraction is followed by a period of relaxation, allowing the ventricles to refill with blood. Following this, a short relative refractory period allows for limited excitability, but under normal conditions, the heart cannot be tetanized. This property distinguishes cardiac muscle from skeletal muscle and guarantees rhythmic, coordinated pumping action.