CHAPTER 21

CARDIAC ELECTROPHYSIOLOGY AND THE ELECTROCARDIOGRAM

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Different cardiac cells serve different and very specialized functions, but all are electrically active. The heart's electrical signal normally originates in a group of cells high in the right atrium that depolarize spontaneously; it then spreads throughout the heart from cell to cell (Fig. 21-1). As this action potential propagates through the heart—sometimes carried by cells that form specialized conducting pathways and sometimes by the very cells that generate the force of contraction—it assumes different appearances within the different cardiac cells (Fig. 21-2). Based on the speed of the upstroke, we can characterize action potentials as either **slow** (sinoatrial and atrioventricular nodes) or **fast** (atrial myocytes, Purkinje fibers, and ventricular myocytes).

Because the excitation of cardiac myocytes triggers contraction—a process called *excitation-contraction coupling* (see p. 229)—the propagation of action potentials must be carefully timed to synchronize ventricular contraction and thereby optimize the ejection of blood. This chapter focuses on the membrane currents responsible for the generation and transmission of action potentials in heart tissue. We also examine how to record the heart's electrical flow by placing electrodes on the surface of the body to create one of the simplest and yet one of the most useful diagnostic tools available to the clinician—the electrocardiogram.

ELECTROPHYSIOLOGY OF CARDIAC CELLS

The cardiac action potential starts in specialized muscle cells of the sinoatrial node and then propagates in an orderly fashion throughout the heart

The cardiac action potential originates in a group of cells called the **sinoatrial (SA) node** (see Fig. 21-1), located in the right atrium. These cells depolarize spontaneously and fire action potentials at a regular, intrinsic rate that is usually between 60 and 100 times per minute for an individual at rest. Both parasympathetic and sympathetic neural input can modulate this intrinsic **pacemaker** activity, or *automaticity* (see pp. 397–398).

Because cardiac cells are electrically coupled through gap junctions (Fig. 21-3*A*), the action potential propagates from cell to cell in the same way that an action potential in nerve conducts along a single long axon. A spontaneous action potential originating in the SA node will conduct from cell to cell throughout the right atrial muscle and spread to the left atrium. The existence of discrete conducting pathways in the atria is still disputed. About one tenth of a second after its origination, the signal arrives at the **atrioventricular (AV) node** (see Fig. 21-1). The impulse does not spread directly from the atria to the ventricles because of the presence of a fibrous **atrioventricular ring.** Instead, the only available pathway is for the impulse to travel from the AV node to the **His-Purkinje fiber system,** a network of specialized conducting cells that carries the signal to the muscle of both ventricles.

The cardiac action potential conducts from cell to cell via gap junctions

The electrical influence of one cardiac cell on another depends on the voltage difference between the cells and on the resistance of the gap junction connecting them. A **gap junction** (see p. 205) is an **electrical synapse** (see Fig. 21-3*A*) that permits electrical current to flow between neighboring cells. According to Ohm's law, the current flowing between cell A and the adjacent cell B (I_{AB}) is proportional to the voltage difference between the two cells (ΔV_{AB}) but inversely proportional to the electrical resistance between them (R_{AB}):

$$I_{AB} = \frac{V_A - V_B}{R_{AB}} = \frac{\Delta V_{AB}}{R_{AB}} \qquad (21\text{-}1)$$

When R_{AB} is very small (i.e., when the cells are tightly coupled), the gap junctions are minimal barriers to the flow of depolarizing current.

Imagine that several interconnected cells are initially all at their normal resting potentials (see Fig. 21-3*B*). An action potential propagating from the left of cell A now injects depolarizing current into cell A. As a result, the cell depolarizes to V_A, which is now somewhat positive compared with V_B. Thus, a small depolarizing current (i.e., positive charges) will also move from cell A to cell B and depolarize cell B. In turn, current flowing from cell B will then depolarize cell C. By this process, the cells closest to the current source undergo the greatest depolarization.

Imagine that the injected current, coming from the active region of the heart to the left, depolarizes cell A just to its threshold (see Fig. 21-3*C*, red curve) but that cell A has not yet fired an action potential. At this instant, the current passing from cell A to cell B cannot bring cell B to its threshold. Of course, cell A will eventually fire an action potential and, in the process, depolarize enough to inject enough current into cell B to raise cell B to its threshold. Thus, the action potential propagates down the chain of cells, but relatively slowly. On the other hand, if the active region to the left injects *more* current into cell A (see Fig. 21-3*C*, blue curve)—producing a larger depolarization in cell A—the current passing from cell A to cell B will be greater and sufficient to depolarize cell B beyond its voltage threshold for a regenerative action potential. However, at this instant, the current passing from cell B to cell C is still not sufficient to trigger an action potential in cell C. That will have to wait until the active region moves closer to cell C, but the wait is not as long as in the first example (red curve in Fig. 21-3*C*). Thus, the action potential propagates more rapidly in this second example (blue curve in Fig. 21-3*C*).

In principle, we could make the action potential propagate more rapidly down the chain of cells in two ways. First, we could allow more ion channels to open in the active region of the heart, so that depolarizing current is larger (blue curve in Fig. 21-3*C*). Second, we could lower the threshold for the regenerative action potential ("more negative threshold" in Fig. 21-3*C*), so that even the small current represented by the red curve is now sufficient to trigger cell B.

Just as in a nerve axon conducting an action potential, the intracellular and extracellular currents in heart muscle must be equal and opposite. In the active region of the heart (to the left of cell A in Fig. 21-3*B*), cells have reached threshold and their action potentials provide the *source* of current that depolarizes cells that are approaching threshold (e.g., cells A and B). As cell A itself is depolarizing to and beyond threshold, its Na⁺ and Ca²⁺ channels are opening, enabling these cations (i.e., positive charge) to enter. The positive charge that enters cell A not only depolarizes cell A but also produces a flow of positive charge to cell B—**intracellular current.** This flow of positive charge discharges the membrane capacitance of cell B, thereby depolarizing cell B and releasing extracellular positive charges that had been associated with the membrane. The movement of this extracellular positive charge from around cell B toward the extracellular region around cell A constitutes the **extracellular current.** The flow of intracellular current from cell A to cell B and the flow of extracellular current from around cell B to around cell A are equal and opposite. It is the flow of this *extracellular* current in the heart that gives rise to an instantaneous electrical vector, which changes with time. Each point on an **electrocardiogram (ECG)** is the sum of the many such electrical vectors, generated by the many cells of the heart.

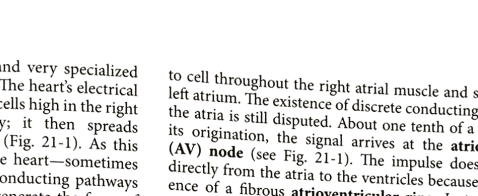
Interatrial tract (Bachman's bundle) to left atrium
Aorta
AV node
Superior vena cava
Bundle of His
SA node
Mainstem, left bundle branch
Anterosuperior left bundle branch
Internodal pathways
Posteroinferior left bundle branch
Atrial muscle
Purkinje fibers
Right bundle branch
Ventricular muscle

Figure 21-1 Conduction pathways through the heart. A section through the long axis of the heart is shown.

Cardiac action potentials have as many as five distinctive phases

The initiation time, shape, and duration of the action potential are distinctive for different parts of the heart, reflecting their different functions (see Fig. 21-2). These distinctions arise because the myocytes in each region of the heart have a characteristic set of channels and anatomy. Underlying cardiac action potentials are four major time-dependent and voltage-gated membrane currents (Table 21-1): N21-1

1. The **Na⁺ current** (I_{Na}) is responsible for the rapid **depolarizing** phase of the action potential in atrial and ventricular muscle and in Purkinje fibers.