PART I

Disorders of the Heart Rhythm: Basic Principles

CHAPTER 1

The Cardiac Electrical System

The heart spontaneously generates electrical impulses, and these electrical impulses are vital to all cardiac functions. On a basic level, by controlling the flux of calcium ions across the cardiac cell membrane, these electrical impulses trigger cardiac muscle contraction. On a higher level, the heart's electrical impulses organize the sequence of muscle contraction during each heartbeat, important for optimizing the cardiac stroke volume. Finally, the pattern and timing of these impulses determine the heart rhythm. Derangements in this rhythm often impair the heart's ability to pump enough blood to meet the body's demands.

Thus, the heart's electrical system is fundamental to cardiac function. The study of the electrical system of the heart is called cardiac electrophysiology, and the main concern of the field of electrophysiology is with the mechanisms and therapy of cardiac arrhythmias. The electrophysiology study is the most definitive method of evaluating the cardiac electrical system; it is the subject of this book.

As an introduction to the field of electrophysiology and to the electrophysiology study, this chapter reviews the anatomy of the cardiac electrical system and describes how the vital electrical impulse is normally generated and propagated.

The anatomy of the heart's electrical system

The heart's electrical impulse originates in the sinoatrial (SA) node, located high in the right atrium near the superior vena cava. The impulse leaves the SA node and spreads radially across both atria. When the impulse reaches the atrioventricular (AV) groove, it encounters the "skeleton of the heart," the fibrous structure to which the valve rings are attached, and that separates the atria from the ventricles. This fibrous structure is electrically inert and acts as an insulator—the electrical

impulse cannot cross this structure. Thus, the electrical impulse would be prevented from crossing over to the ventricular side of the AV groove if not for the specialized AV conducting tissues: the AV node and the bundle of His (Figure 1.1).

As the electrical impulse enters the AV node, its conduction is slowed because of the electrophysiologic properties of the AV nodal tissue. This slowing is reflected in the PR interval on the surface electrocardiogram (ECG). Leaving the AV node, the electrical impulse enters the His bundle, the most proximal part of the rapidly conducting His-Purkinje system. The His bundle penetrates the fibrous skeleton and delivers the impulse to the ventricular side of the AV groove.

Once on the ventricular side, the electrical impulse follows the His bundle as it branches into the right and left bundle branches. Branching of the Purkinje fibers continues distally to the furthermost reaches of the ventricular myocardium. The electrical impulse is thus rapidly distributed throughout the ventricles.

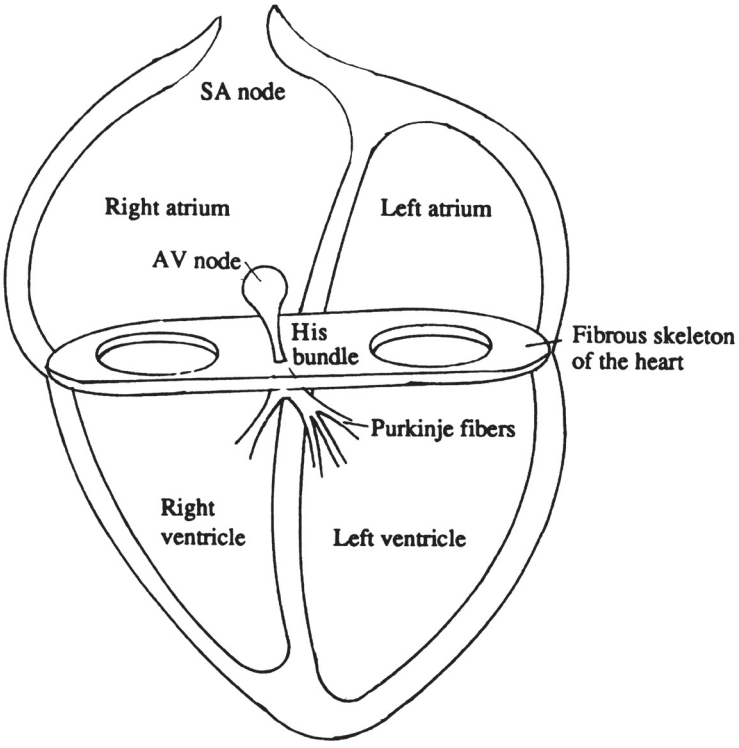

Fig. 1.1 Anatomy of the electrical system of the heart.

Hence, the heart's electrical system is designed to organize the sequence of myocardial contraction with each heartbeat. As the electrical impulse spreads over the atria toward the AV groove, the atria contract. The delay provided by the AV node allows for complete atrial emptying before the electrical impulse reaches the ventricles. Once the impulse leaves the AV node, it is distributed rapidly throughout the ventricular muscle by the Purkinje fibers, providing for brisk and orderly ventricular contraction.

We next consider the character of the electrical impulse, its generation, and propagation.

The cardiac action potential

The cardiac action potential is one of the most despised and misunderstood topics in cardiology. The fact that electrophysiologists claim to understand it is also a leading cause of the mystique that surrounds them and their favorite test, the electrophysiology study. Because the purpose of this book is to debunk the mystery of electrophysiology studies, we must confront the action potential and learn to understand it. Fortunately, this is far easier than legend would have it.

Although most of us would like to think of cardiac arrhythmias as an irritation or "itch" of the heart (and of antiarrhythmic drugs as a balm or a salve that soothes the itch), this conceptualization of arrhythmias is wrong and leads to the faulty management of patients with arrhythmias. In fact, the behavior of the heart's electrical impulse and of the cardiac rhythm is largely determined by the shape of the action potential; the effect of antiarrhythmic drugs is determined by how they change that shape.

The inside of the cardiac cell, like all living cells, has a negative electrical charge compared to the outside of the cell. The resulting voltage difference across the cell membrane is called the *transmembrane potential*. The resting transmembrane potential (which is −80 to −90 mV in cardiac muscle) is the result of an accumulation of negatively charged molecules (called ions) within the cell. Most cells are happy with this arrangement and live out their lives without considering any other possibilities.

Cardiac cells, however, are excitable cells. When excitable cells are stimulated appropriately, tiny pores or channels in the cell membrane open and close sequentially in a stereotyped fashion. The opening of these channels allows ions to travel back and forth across the cell membrane (again in a stereotyped fashion), leading to patterned changes in the transmembrane potential. When these stereotypic voltage changes are graphed against time, the result is the cardiac action

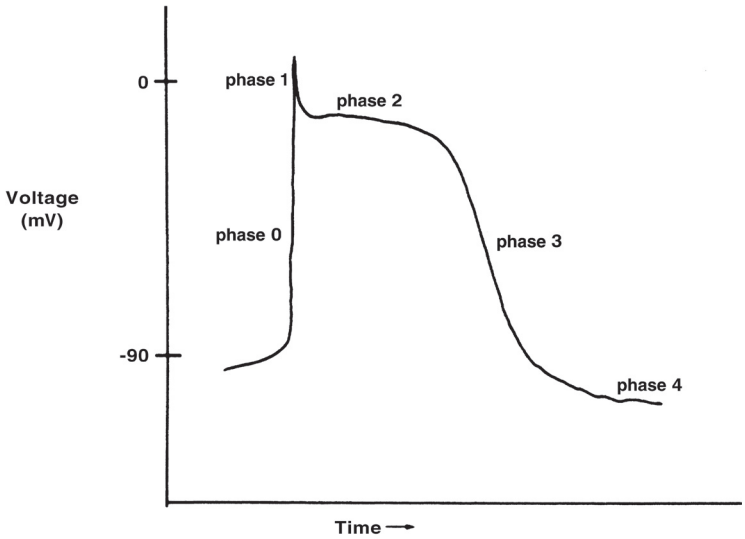

Fig. 1.2 The cardiac action potential.

potential (Figure 1.2). The action potential is thus a reflection of the electrical activity of a single cardiac cell.

As can be seen in Figure 1.2, the action potential is classically divided into five phases. However, it is most helpful to consider the action potential in terms of three general phases: depolarization, repolarization, and the resting phase.

Depolarization

The depolarization phase (phase 0) is where the action of the action potential is. Depolarization occurs when the rapid sodium channels in the cell membrane are stimulated to open. When this happens, positively charged sodium ions rush into the cell, causing a rapid, positively directed change in the transmembrane potential. The resultant voltage spike is called *depolarization*. When we speak of the heart's electrical impulse, we are speaking of this depolarization.

Depolarization of one cell tends to cause adjacent cardiac cells to depolarize, because the voltage spike of a cell's depolarization causes the sodium channels in the nearby cells to open. Thus, once a cardiac cell is stimulated to depolarize, the wave of depolarization (the electrical impulse) is propagated across the heart, cell by cell.

Further, the speed of depolarization of a cell (reflected by the slope of phase 0 of the action potential) determines how soon the next cell will

depolarize, and thus determines the speed at which the electrical impulse is propagated across the heart. If we do something to change the speed at which sodium ions enter the cell (and thus change the slope of phase 0), we therefore change the speed of conduction (the conduction velocity) of cardiac tissue.

Repolarization

Once a cell is depolarized, it cannot be depolarized again until the ionic fluxes that occur during depolarization are reversed. The process of getting the ions back to where they started is called *repolarization*. The repolarization of the cardiac cell roughly corresponds to phases 1 through 3 (i.e., the width) of the action potential. Because a second depolarization cannot take place until repolarization occurs, the time from the end of phase 0 to late in phase 3 is called the *refractory period* of cardiac tissue.

Repolarization of the cardiac cells is complex and poorly understood. Fortunately, the main ideas behind repolarization are simple: 1) repolarization returns the cardiac action potential to the resting transmembrane potential; 2) it takes time to do this; 3) the time that it takes to do this, roughly corresponding to the width of the action potential, is the refractory period of cardiac tissue.

There is an additional point of interest regarding repolarization of the cardiac action potential. Phase 2 of the action potential, the so-called plateau phase, can be viewed as interrupting and prolonging the repolarization that begins in phase 1. This plateau phase, which is unique to cardiac cells (e.g., it is not seen in nerve cells), gives duration to the cardiac potential. It is mediated by the slow calcium channels, which allow positively charged calcium ions to slowly enter the cell, thus interrupting repolarization and prolonging the refractory period. The calcium channels have other important effects in electrophysiology, as we will see.

The resting phase

For most cardiac cells, the resting phase (the period of time between action potentials, corresponding to phase 4) is quiescent, and there is no net movement of ions across the cell membrane.

For some cells, however, the so-called resting phase is not quiescent. In these cells, there is leakage of ions back and forth across the cell membrane during phase 4 in such a way as to cause a gradual increase in transmembrane potential (Figure 1.3). When the transmembrane potential is high enough (i.e., when it reaches the threshold voltage), the appropriate channels are activated to cause the cell to depolarize.

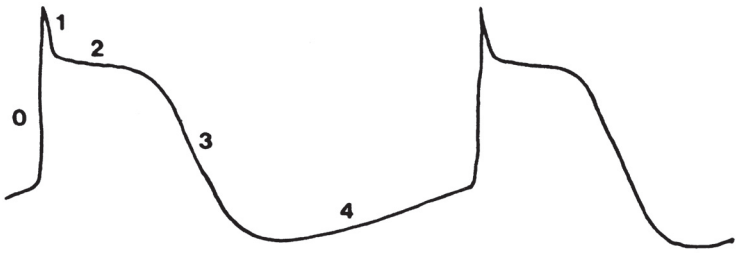

Fig. 1.3 Automaticity. In some cardiac cells, there is a leakage of ions across the cell membrane during phase 4 in such a way as to cause a gradual, positively directed change in transmembrane voltage. When the transmembrane voltage becomes sufficiently positive, the appropriate channels are activated to automatically generate another action potential. This spontaneous generation of action potentials due to phase 4 activity is called automaticity.

Because this depolarization, like any depolarization, can stimulate nearby cells to depolarize in turn, the spontaneously generated electrical impulse can be propagated across the heart. This phase 4 activity, which leads to spontaneous depolarization, is called *automaticity*.

Automaticity is the mechanism by which the normal heart rhythm is generated. Cells in the SA node (the pacemaker of the heart) normally have the fastest phase 4 activity within the heart. The spontaneously occurring action potentials in the SA node are propagated as described earlier, resulting in normal sinus rhythm. If, for any reason, the automaticity of the sinus node should fail, there are usually secondary pacemaker cells (often located in the AV junction) that take over the pacemaker function of the heart, but at a slower rate.

Thus, the shape of the action potential determines the conduction velocity, refractory period, and automaticity of cardiac tissue. Later we shall see how these three electrophysiologic characteristics directly affect the mechanisms of cardiac rhythms, both normal and abnormal. To a large extent, the purpose of the electrophysiology study is to assess the conduction velocities, refractory periods, and automaticity of various portions of the heart's electrical system.

Localized variations in the heart's electrical system

In understanding cardiac arrhythmias, it is important to consider two issues involving localized differences in the heart's electrical system: variations in the action potential and variations in autonomic innervation.

Localized differences in the action potential

The cardiac action potential does not have the same shape in every cell of the heart's electrical system. The action potential we have been using as a model (see Figure 1.2) is a typical Purkinje fiber action potential. Figure 1.4 shows representative action potentials from several key locations of the heart—note the differences in shape.

The action potentials that differ most radically from the Purkinje fiber model are found in the SA node and AV node. Note that the action potentials from these tissues have slow instead of rapid depolarization phases (phase 0). This slow depolarization occurs because SA nodal and AV nodal tissues lack the rapid sodium channels responsible for the rapid depolarization phase (phase 0) seen in other cardiac tissues. In fact, the SA and AV nodes are thought to be dependent entirely on the slow calcium channel for depolarization. Because the speed of depolarization determines conduction velocity, the SA and AV nodes conduct electrical impulses slowly. The slow conduction in the AV node is reflected in the PR interval on the surface ECG (see Figure 1.5).

Localized differences in autonomic innervation

In general, an increase in sympathetic tone causes enhanced automaticity (pacemaker cells fire more rapidly), increased conduction velocity (electrical impulses are propagated more rapidly), and decreased action potential duration and thus decreased refractory periods (cells are ready for repeated depolarizations more quickly). Parasympathetic tone has

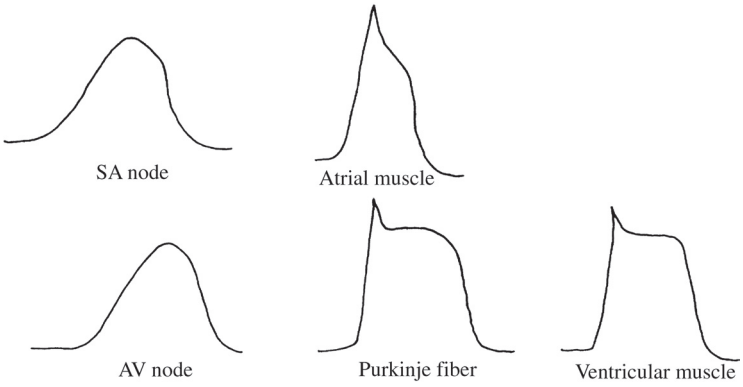

Fig. 1.4 Localized differences in the cardiac action potential. Cardiac action potentials from different locations within the heart have different shapes. These differences account for the differences seen in electrophysiologic properties in various tissues within the heart.

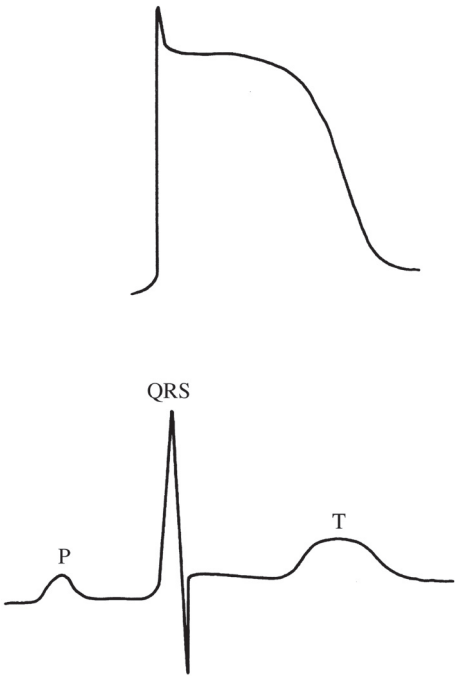

Fig. 1.5 Relationship between the ventricular action potential (*top*) and the surface ECG (*bottom*). The rapid depolarization phase (phase 0) of the action potential is reflected in the QRS complex on the surface ECG. Because phase 0 is almost instantaneous, the QRS complex yields directional information on ventricular depolarization. In contrast, the repolarization portion of the action potential has significant duration (phases 2 and 3). Consequently, the portion of the surface ECG that reflects repolarization (the ST segment and the T wave) yields little directional information. PR interval, beginning of P to beginning of QRS; ST segment, end of QRS to beginning of T; QT interval, beginning of QRS to end of T.

the opposite effect (i.e., depressed automaticity, decreased conduction velocity, and increased refractory periods).

Sympathetic and parasympathetic fibers richly innervate both the SA node and the AV node. In the remainder of the heart's electrical system, while sympathetic innervation is abundant, parasympathetic innervation is relatively sparse. Thus, changes in parasympathetic tone have a relatively greater effect on the SA nodal and AV nodal tissues than on other tissues of the heart. This fact has implications for the diagnosis and treatment of some heart rhythm disturbances.

Relationship between action potential and surface ECG

The cardiac action potential represents the electrical activity of a single cardiac cell. The surface ECG reflects the electrical activity of the entire heart—essentially, it represents the sum of all the action potentials of all cardiac cells. Consequently, the information one can glean from the surface ECG derives from the characteristics of the action potential (Figure 1.5).

For most cardiac cells, the depolarization phase of the action potential is essentially instantaneous (occurring in 1 to 3 msec) and occurs sequentially, from cell to cell. Thus, the instantaneous wave of depolarization can be followed across the heart by studying the ECG. The P wave represents the depolarization front as it traverses the atria, and the QRS complex tracks the wave of depolarization as it spreads across the ventricles. Changes in the spread of the electrical impulse, such as occur in bundle branch block or in transmural myocardial infarction, can be readily diagnosed. Because the depolarization phase of the action potential is relatively instantaneous, the P wave and the QRS complex can yield specific directional information (i.e., information on the sequence of depolarization of cardiac muscle).

In contrast, the repolarization phase of the action potential is not instantaneous—indeed, repolarization has significant duration. Thus, while depolarization occurs from cell to cell sequentially, repolarization occurs in many cardiac cells simultaneously. For this reason, the ST segment and T wave (the portions of the surface ECG that reflect ventricular repolarization) give little directional information, and abnormalities in the ST segments and T waves are most often (and quite properly) interpreted as being nonspecific. The QT interval represents the time of repolarization of the ventricular myocardium and reflects the average action potential duration of ventricular muscle.