Disorders of cardiac rate and rhythm represent major causes of mortality and morbidity in developed countries. Sudden cardiac death, defined as death within 1 hour of an unexpected change in cardiovascular status, kills more than 300,000 people each year in the United States (29), whereas nonlethal arrhythmias account for much additional disability. Atrial fibrillation, a leading cause of cerebrovascular accidents (stroke), occurs in >1% of patients over the age of 60, and ~10% in those over 70 years of age (30). These epidemiologic considerations alone would justify teaching this material to health professionals. There is, however, an additional reason why this topic is of considerable interest. This is the now solid intellectual link between clinical arrhythmias and the molecular behavior of the voltage-gated ion channels of the heart, a connection that has been illuminated by recent discoveries regarding the molecular basis of both the classic Hodgkin-Huxley characterization of ion channel gating (1, 3, 6, 9–10, 13–19, 21–23, 26, 28, 31, 42) and the heritable long-QT syndromes (2, 4–5, 11–12, 20, 25, 27, 32–41, 43–45). This article highlights the physiology of the arrhythmias, a subject that I have taught to medical, dental, and graduate students since 1965.

A serious challenge in presenting the topic of cardiac arrhythmias is the current status of therapy. Until a few years ago, efforts to prevent and treat arrhythmias centered on antiarrhythmic drugs, which provided a clinical “relevance” to this physiology. However, the pharmacological approach to antiarrhythmic therapy has recently encountered serious problems. On the one hand, interventional therapy—generally, radiofrequency ablation that physically destroys abnormal conduction pathways—has made it possible to cure a number of supraventricular arrhythmias, notably those associated with abnormal atrioventricular pathways [Wolff-Parkinson-White syndrome and atrioventricular (AV) nodal reentrant tachycardias], and implantable defibrillators have been shown to prevent sudden death in many populations at high risk for lethal arrhythmias. On the other hand, most antiarrhythmic drugs are now known to be less effective and far more dangerous than once believed. Especially dramatic was the CAST (Cardiac Arrhythmia Suppression Trial), which, to the surprise of many, demonstrated that antiarrhythmic drugs that reduce the frequency of premature ventricular beats in a high-risk population not only fail to prevent sudden death but actually increase overall mortality (7–8). These findings, which have been confirmed in additional trials, have led to a shift (at least for the moment) away from antiarrhythmic drug therapy. The “proarrhythmic” effects of most currently available antiarrhythmic drugs make it unlikely that most physicians will be prescribing these agents, which at this time seems best left to the arrhythmia specialists. These considerations, while taking some of the “edge” off learning arrhythmogenic mechanisms, do not obviate the need to teach this subject. It remains essential for our students to be able to diagnose common arrhythmias, to distinguish between arrhythmias that are nuisances best left alone and those associated with significant long-term morbidity, to identify arrhythmias that are best managed by such “definitive” therapy as radiofrequency ablation, and to recognize arrhythmias that are life threatening and therefore require immediate, expert management.

Teaching about arrhythmias also reinforces the student’s understanding of the normal electrical activation of the heart and those aspects of basic electrophysiology that, when altered by disease, are responsible for cardiac arrhythmias. An expanded discussion of my approach to this topic, written for
NORMAL ACTIVATION OF THE HEART

Each normal cardiac cycle begins when spontaneous depolarization of the SA (sinoatrial or sinus) node pacemaker generates an electrical signal that is conducted throughout the heart (21). Propagation of this signal occurs when the electronegativity of depolarized cells opens voltage-gated ion channels in the plasma membrane of nearby resting cardiac myocytes. The resulting action potentials, although differing in various regions of the heart, all begin when an inward flux of cations depolarizes the plasma membrane. Other families of ion channels restore the normal resting potential and thereby repolarize the heart (23).

Working myocardial cells and the rapidly conducting fibers of the His-Purkinje system are depolarized by inward sodium currents, whereas depolarization of the SA and AV nodes depends on the opening of a smaller number of calcium channels. In the atria and ventricles, these depolarizing ion currents generate potential differences sufficiently large to be recorded at the body surface as the clinical electrocardiogram (ECG); atrial depolarization gives rise to the P wave and ventricular depolarization to the QRS complex. (The T wave, not discussed further in this article, is inscribed during ventricular repolarization.) The depolarizing currents generated by the rapidly conducting fibers of the AV bundle (bundle of His, or common bundle) and the Purkinje fibers that line the endocardial surfaces of the ventricles are too small to be recorded on the ECG. Also too small to be seen on the ECG are the depolarizing currents generated in the SA node, which contribute to the sinus pacemaker activity that initiates each cardiac cycle, and the slow depolarizations in the AV node, which are responsible for a delay in AV conduction that controls the relative timing of atrial and ventricular systole and gives rise to the long P-R interval in the normal ECG.

ARRHYTHMOGENIC MECHANISMS

Disorders in cardiac rate and rhythm, the arrhythmias, were first defined clinically in terms of abnormalities of the arterial pulse, which for many millennia had been used to make diagnoses. Hippocrates noted that a slow pulse in elderly men heralded sudden death, which almost certainly reflected the relationship between AV block and asystole. Galen described a patient who died a few months after his pulse became irregular, most likely caused by atrial fibrillation complicating rheumatic or hypertensive heart disease. In the late 19th century, simultaneous recordings of arterial and jugular pulsations using the smoked drum kymograph provided remarkable insights into arrhythmogenic mechanisms and allowed Wenckebach to describe the features sometimes seen in the AV block that bears his name.

This field matured at the beginning of the 20th century, when Einthoven's invention of the string galvanometers made it possible to record precisely the depolarization of the atria (P wave) and ventricles (QRS complex) using electrodes placed on the body surface. Within a few decades a vast literature had described the major clinical arrhythmias, and by the 1950s, most of the physiological mechanisms that disturb impulse formation and impulse propagation in the human heart had been identified (24). Subsequent advances in basic electrophysiology, first using micro electrodes to record intracellular potentials and then patch-clamp technology to measure the opening and closing of single ion channels, carried this understanding to the cellular and molecular levels. More recently, the techniques of molecular biology have characterized arrhythmogenic mechanisms in terms of the molecular structures of specific classes of voltage-gated ion channels.

General Types of Arrhythmogenic Mechanism

Identification of the mechanism responsible for an arrhythmia in a specific patient is generally difficult, and often impossible, because several abnormalities can produce a single electrocardiographic pattern. Sinus bradycardia, for example, can be caused by slowed diastolic depolarization, hyperpolarization, and increased threshold (Fig. 1). Tachycardias are caused not only by accelerated pacemaker activity but also by a phenomenon called reentry, in which a single impulse generates more than one response by exciting one or more regions of the heart. Reentry itself can be caused by a number of different mechanisms. These include triggered automaticity, which can be caused by both early and late after depolarizations (Fig. 2). Another cause of reentry is disruption of the spread of the wave of depolarization as it is propagated through the heart, for example, when scarring or localized areas of cell damage slow conduction and
FIG. 1. Three possible mechanisms can slow the sinoatrial (SA) node pacemaker (solid line, control; dashed line, slowed): a decreased rate of diastolic depolarization (A), diastolic hyperpolarization (B), and increased threshold (C). More than one of these changes may be induced by a given intervention. Pacemaker discharge can be accelerated by opposite changes in any or all of these variables (increased rate of diastolic depolarization, diastolic depolarization, lowered threshold). [Modified from Katz (21).]

FIG. 2. Different types of afterdepolarizations. A: early afterdepolarizations showing a subthreshold afterdepolarization that does not reach threshold (1) and larger early afterdepolarizations that cause a single (2) and repetitive (3-4-5) triggered depolarizations. B: late afterdepolarizations showing a subthreshold afterdepolarization that does not reach threshold (1) and late afterdepolarizations that reach threshold so as to produce one (2) or a series (3-4-5) of triggered depolarizations. [Reprinted from Katz (21) with permission.]
cause unidirectional block (Fig. 3). Reentry is also seen when atrial or ventricular dilatation increases the length of the conduction pathways, which can allow a wave front to loop back to excite tissue that it had previously depolarized. Several causes of slowed conduction that predispose to reentrant arrhythmias have been identified at the cellular and molecular level (Table 1). These include abnormal gating of the ion channels of the heart, which occurs when resting depolarization in an ischemic region of the ventricle slows conduction by inhibiting sodium channel opening (activation). Resting depolarization also generates injury currents that can allow the abnormally depolarized cells to activate other, normal regions (Fig. 4). Abnormalities in channel recovery (reactivation), by altering the opening of depolarizing potassium channels, can cause local changes in action potential duration and refractoriness that lead directly to reentry, as shown in Fig. 5. Inhomogeneities of repolarization also provide an important substrate for the reentrant mechanisms depicted in Fig. 3. Two special mechanisms that involve reentry in circuits in the AV node cause paroxysmal supraventricular tachycardias (Figs. 6 and 7). A recently discovered class of arrhythmogenic mechanisms is seen in patients with inherited molecular abnormalities. These include the long-QT syndromes, which are caused by abnormal ion-channel structure (2, 4–5, 11–12, 20, 25, 27, 32–41, 43–45), and several familial dilated cardiomyopathies that include conduction system disease. All

**TABLE 1**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Structural and Functional Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate of depolarization</td>
<td>Rate and number of Na(^+) or Ca(^{2+}) channel openings</td>
</tr>
<tr>
<td>Action potential amplitude</td>
<td>Maximum inward current through open Na(^+) or Ca(^{2+}) channels</td>
</tr>
<tr>
<td>Threshold</td>
<td>Extent of depolarization needed to open Na(^+) or Ca(^{2+}) channels</td>
</tr>
<tr>
<td>Electrical resistances</td>
<td></td>
</tr>
<tr>
<td>Longitudinal Extracellular</td>
<td>Volume and conductivity of extracellular fluid, fibrosis</td>
</tr>
<tr>
<td>Intracellular</td>
<td>Number of open connexin hexamers in the intercalated discs</td>
</tr>
<tr>
<td>Transverse</td>
<td>Plasma membrane conductivity and capacitance</td>
</tr>
</tbody>
</table>

FIG. 3. Reentrant circuits established where a Purkinje fiber impinges on the ventricular myocardium (a) and within a strand of cardiac muscle (b). In both situations a region of decremental conduction with unidirectional block (A–B) prevents antegrade conduction of the normal impulse (arrow 1) but allows this impulse to propagate slowly through the depressed region in the retrograde direction (dotted line). After a delay, the retrograde impulse can reenter the myocardium proximal to the region of decremental conduction; if this occurs after the tissue proximal to the depressed area has recovered from the first impulse, the retrograde impulse can initiate a premature systole (arrow 2). [Reprinted from Katz (21) with permission.]
of these arrhythmogenic mechanisms can be exacerbated by neurotransmitters, metabolites, and membrane poisons; the latter, unfortunately, include most antiarrhythmic drugs.

The diversity of these arrhythmogenic mechanisms makes it difficult to teach this material beyond providing “lists,” such as that in Table 2. A major problem in relating such lists to clinical arrhythmias is the fact that many arrhythmogenic mechanisms have more than one underlying cause. As already noted, several abnormalities can slow pacemaker activity (Fig. 1). Another example, inhomogeneities in action potential gating, can be caused by anatomic abnormalities, such as when cells are encased in fibrous tissue; metabolic abnormalities, such as those that occur in ischemic tissue; drugs; and molecular abnormalities, such as those in the long-QT syndromes.

The arrhythmogenic mechanisms diagrammed in Figs. 1–5 and listed in Tables 1 and 2 are rarely apparent at the bedside. For this reason, the cause of an arrhythmia is usually inferred from the clinical context. When the cause of a supraventricular tachycardia is being determined, for example, if the patient has digitalis toxicity, the mechanism is likely to be an accelerated AV nodal pacemaker (caused by digitalis), whereas paroxysmal behavior (sudden onset and offset of the arrhythmia) suggests reentry involving the AV node, as shown in Figs. 6 and 7. If the baseline ECG in a patient with a paroxysmal supraventricular tachycardia shows a short P-R interval and slurred QRS upstroke (called a delta wave), the underlying abnormality is almost certainly reentry through an accessory pathway (see Fig. 7). In some settings, such as ventricular tachyarrhythmias in patients immediately following an acute myocardial infarction, the most common cause is reentry caused by injury currents that arise in ischemic, but not yet dead, myocardium (Fig. 4). Similar arrhythmias in a patient with end-stage...
heart failure, on the other hand, are probably caused by disorganization of the wave of depolarization as it passes through areas of fibrosis in the diseased ventricle. Sinus bradycardia and AV block after a posterior or inferior myocardial infarction are usually caused by reflex parasympathetic stimulation (the von Bezold-Jarisch reflex), whereas AV block after a massive anterior infarction is generally the result of damage to the bundle of His and bundle branches in an infarcted interventricular septum. Clinical “rules” of this sort are difficult to teach in a basic science course and for all practical purposes should be left to later parts of the curriculum.

TABLE 2
A simple classification of arrhythmogenic mechanisms and some putative electrophysiological causes

<table>
<thead>
<tr>
<th>I. Bradyarrhythmias</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Slowed pacemaker activity</td>
</tr>
<tr>
<td>1. Decreased rate of diastolic depolarization</td>
</tr>
<tr>
<td>2. Diastolic hyperpolarization</td>
</tr>
<tr>
<td>3. Increased threshold</td>
</tr>
<tr>
<td>B. Depressed (slowed) impulse conduction</td>
</tr>
<tr>
<td>1. SA block</td>
</tr>
<tr>
<td>2. AV block</td>
</tr>
<tr>
<td>a. In AV node</td>
</tr>
<tr>
<td>b. In AV bundle or bundle branches</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>II. Tachyarrhythmias</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Accelerated pacemaker activity</td>
</tr>
<tr>
<td>1. Increased rate of diastolic depolarization</td>
</tr>
<tr>
<td>2. Diastolic depolarization</td>
</tr>
<tr>
<td>3. Decreased threshold</td>
</tr>
<tr>
<td>B. Triggered depolarizations (afterdepolarizations)</td>
</tr>
<tr>
<td>1. Early afterdepolarizations</td>
</tr>
<tr>
<td>2. Late afterdepolarizations</td>
</tr>
<tr>
<td>C. Reentry</td>
</tr>
<tr>
<td>1. Abnormal conduction (decremental conduction and unidirectional block)</td>
</tr>
<tr>
<td>2. Inhomogeneous action potential characteristics</td>
</tr>
<tr>
<td>a. Inhomogeneous resting potential</td>
</tr>
<tr>
<td>i. Regional ischemia</td>
</tr>
<tr>
<td>ii. Scarring</td>
</tr>
<tr>
<td>iii. Localized expression of abnormal ion channels</td>
</tr>
<tr>
<td>b. Inhomogeneous depolarization</td>
</tr>
<tr>
<td>i. Regional ischemia</td>
</tr>
<tr>
<td>ii. Scarring</td>
</tr>
<tr>
<td>iii. Localized expression of abnormal ion channels</td>
</tr>
<tr>
<td>c. Inhomogeneous repolarization and refractoriness</td>
</tr>
<tr>
<td>i. Regional ischemia</td>
</tr>
<tr>
<td>ii. Scarring</td>
</tr>
<tr>
<td>iii. Localized expression of abnormal ion channels</td>
</tr>
<tr>
<td>3. Abnormal conducting structures</td>
</tr>
<tr>
<td>a. Dual pathways in the AV node</td>
</tr>
<tr>
<td>b. Accessory pathway (“bundle of Kent”)</td>
</tr>
</tbody>
</table>

SA, sinoatrial; AV, atrioventricular.
Examples of Common Clinical Arrhythmias

In view of the frequent occurrence of arrhythmias (about one-half of most medical students in a class will exhibit occasional premature atrial or ventricular systoles on a 24-hour ECG recording), I believe it is important to teach a simple classification of the clinical arrhythmias, such as that provided in Table 3. The most obvious way to begin any such classification is to ask whether the rate is too slow or too fast, i.e., whether the problem is bradycardia or tachycardia. In cases in which the arrhythmia is not sustained, “dropped” (missing) beats can be included among the bradycardias and “extra” beats among the tachycardias. It must be emphasized, however, that a single mechanism, such as depressed conduction, can cause both bradycardia and tachycardia (the latter by favoring reentry).

The classification in Table 3 includes many arrhythmias whose features cannot be taught effectively in the time usually allotted to this material in a physiology course. Arrhythmias that I generally highlight are sinus bradycardia and sinus tachycardia, which fit well with descriptions of pacemaker currents and the effects of autonomic mediators on voltage-gated ion channels in the SA and AV nodes taught elsewhere in most curricula. These topics are also important because they set the stage for material to be given in pharmacology courses.

In presenting the bradyarrhythmias, it is easiest to highlight AV block; sinoatrial block is rather arcane and best taught in a clinical context. The concepts of first-, second-, and third-degree AV block, which depend on the relationships between P waves and QRS complexes, are readily understood by students. Also important are Mobitz I and Mobitz II second-degree AV block, which can be related to functional block in the AV node (Mobitz I) and anatomic block in the His-Purkinje system (Mobitz II), respectively. An example of the Wenckebach phenomenon, which characterizes Mobitz I second-degree AV block, is provided later in this article. I present Mobitz I block as caused by “physiological/pharmacological” depression of conduction by the calcium channel-dependent cells of the AV node, where the normally slow conduction is highly regulated and easily depressed, and Mobitz II as “anatomic” block in the sodium channel-dependent cells of the AV bundle and bundle branches, where conduction failure reflects damage to these normally fast-conducting structures.

There is much more to be taught about the tachyarrhythmias, where discussion of the underlying causes provides an excellent vehicle by which to convey information about arrhythmogenic mechanisms (21). Close scrutiny of the relationship between P waves and QRS complexes in premature atrial, junctional, and ventricular systoles reinforces understanding of impulse propagation within the heart as well as the role of the delay in the AV node—these relationships are generally easier to analyze in single premature beats than during sustained tachycardias. The significance of the prolonged (wide) QRS complex in a ventricular premature depolarization is easily related to loss of the normal synchronicity of right and left ventricular depolarization, which occurs when an impulse arises below the bifurcation of the bundle of His. The prolonged QRS complexes in left and right bundle branch block are also caused by loss of synchronicity, although the underlying mechanism is different.

Because this topic is so large, case presentations such as those provided in Figs. 8–17 are useful in illustrating important underlying mechanisms. Careful analysis of these examples should also stimulate students to

| TABLE 3 |
| A simple classification of clinical arrhythmias |

<table>
<thead>
<tr>
<th>I. Bradyarrhythmias</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. SA node</td>
</tr>
<tr>
<td>1. Sinus bradycardia</td>
</tr>
<tr>
<td>2. Sinoatrial block</td>
</tr>
<tr>
<td>B. AV node and bundle</td>
</tr>
<tr>
<td>1. Atrioventricular block: first, second and third degree</td>
</tr>
<tr>
<td>2. Mobitz I and Mobitz II second-degree AV block: block in the AV node versus block in the AV bundle or bundle branches, the Wenckebach phenomenon.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>II. Tachyarrhythmias</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Premature systoles</td>
</tr>
<tr>
<td>1. Atrial</td>
</tr>
<tr>
<td>2. Junctional</td>
</tr>
<tr>
<td>3. Ventricular</td>
</tr>
<tr>
<td>B. Tachycardias</td>
</tr>
<tr>
<td>1. Supraventricular</td>
</tr>
<tr>
<td>a. Sinus</td>
</tr>
<tr>
<td>b. Atrial</td>
</tr>
<tr>
<td>c. Junctional</td>
</tr>
<tr>
<td>2. Ventricular</td>
</tr>
<tr>
<td>C. Flutter and Fibrillation</td>
</tr>
<tr>
<td>1. Atrial</td>
</tr>
<tr>
<td>2. Ventricular</td>
</tr>
</tbody>
</table>
consult physiology texts for additional mechanistic detail, and clinical texts for clinical context.

Having taught electrocardiography to students, house staff, and cardiology trainees since the mid-1960s, I strongly believe that the arrhythmias should be taught in a rigorous physiology course, in which clinical phenomena can be related to underlying mechanisms. Postponing this topic to the clinical curriculum often means that important pathophysiological concepts are either brushed by quickly or not presented mechanistically by expert teachers. I think it a mistake to allow third- and fourth-year medical students to learn the arrhythmias from interns and residents, many of whom lack an understanding of the mechanisms responsible for these potentially lethal disorders.

A PROBLEM SET FOR TEACHING ARRHYTHMIAS

A set of ECGs that illustrate some important arrhythmias is provided in Figs. 8–17. Each of the following case studies includes a set of ECGs and questions and answers that highlight the teaching objectives of a basic science course. Students should be encouraged to examine each of these ECGs to determine the rate and rhythm, P-R interval, QRS duration, and Q-T interval. By convention, these intervals are measured in the limb leads, which were used in the 1930s to establish normal values in several large normal populations. (Intervals are often longer in the chest leads, but because the latter were not standardized until 1950, it was agreed to use limb lead values for these measurements rather than prepare new tables of normal values). If appropriate, students should also be encouraged to calculate mean QRS vectors (electrical axis). To determine the mechanisms of the abnormal rhythms in the following examples, students should begin with the brief narrative descriptions and then answer the questions provided for each case study.

CASE STUDIES

Case 1

Description. The underlying ventricular rhythm is regular and slow (rate = 45 beats/min). Because every QRS is preceded by a P wave, this rhythm is a sinus bradycardia, probably normal in this athletic young man. There is, however, an additional and highly significant underlying abnormality (Fig. 8).

Questions. 1) What is the P-R interval? Is this normal? What does this tell you?

2) What is the QRS duration? Is this normal?

3) Does the QRS begin normally (look in leads I and V4–V6)? What does this tell you?

4) What is likely to have caused all of the abnormalities? What is this called?

5) Patients with this condition can have paroxysmal supraventricular tachycardias. What is the mechanism of these tachycardias and how might they be treated?

Answers to questions. 1) The P-R interval is very short, ~0.08 s, which tells us that the impulse passing from atria to ventricles has not encountered the normal delay caused by the slow, calcium channel-dependent conduction in the AV node. This implies a “short circuit” caused by abnormal conducting fibers that connect atrial and ventricular myocardium.

2) The QRS duration is ~0.12 s, which is prolonged. This tells us that an abnormally long time has elapsed between the onset and end of ventricular depolarization. As you will see, this is not an example of bundle branch block.

3) The QRS complex begins with a slurred upward deflection (clearest in leads I and V4–V6) that, because it resembles the left half of a Greek capital delta, is called a delta wave. This abnormal beginning of the QRS implies that ventricular activation has begun not only too early (“preexcitation,” which causes the short P-R interval) but also in an abnormal location in the ventricles, where conduction is slower than in the more rapidly conducting His-Purkinje system.

4) Preexcitation, characterized by a short P-R interval and delta wave, occurs when an abnormal rapidly conducting pathway connects the atria and ventricles, bypassing the AV node. Once called a “bundle of Kent,” this is now referred to as an “accessory pathway,” and the clinical syndrome is called the “Wolff-Parkinson-White syndrome” (WPW). The QRS is prolonged because ventricular depolarization begins prematurely, caused by the rapid conduction in the accessory pathway, before the normal impulse reaches the ventricles via the His-Purkinje system.
5) WPW can be accompanied by a paroxysmal supraventricular tachycardia that occurs when the two conducting pathways linking the atria and ventricles set up a reentrant arrhythmia in which the impulse goes “down” one pathway and “up” the other. This arrhythmia is usually initiated by an atrial premature systole, in which the impulse first crosses from atria to ventricles via the normal AV nodal pathway (because this pathway has a shorter refractory period than the accessory pathway) and then returns from ventricles to atria via the accessory pathway. Conduction through this reentrant circuit usually occurs at rates of 140–180 min⁻¹. In treating this condition, an effort is made to interrupt this reentrant circuit at its “weak point,” which is conduction of the impulse through the AV node, where calcium-dependent action potentials are susceptible to drugs that inhibit calcium channel opening. These drugs include the β-adrenergic receptor blockers, acetylcholine, adenosine, digitalis, and calcium channel blockers. Whereas all these drugs are rational therapy, each can have harmful side effects. Definitive therapy is to locate and then ablate (destroy) the accessory pathway using radiofrequency energy delivered via an intracardiac electrode catheter.

Case 2

Description. The basic rhythm is regular, but the 10th QRS is premature (Fig. 9). The answers to the following questions should help you to understand the mechanism for the premature systole.

Questions. 1) Is the contour of the premature QRS like the others in this record? What does this tell you about the mechanism responsible for this beat?
2) Is the premature QRS preceded by a P wave? If so, is this a normal P wave?
3) What is the P-R interval of the usual beats? Is this normal? Is this the same as before the premature QRS?
4) What type of premature systole is this? Can you speculate as to its cause?
Answers to questions. 1) Yes. In this premature QRS the ventricles are depolarized by an impulse that enters the ventricles from above the bifurcation of the bundle of His, i.e., via the normal conduction pathway in the His-Purkinje system.

2) Yes, there is a premature P wave that is superimposed on the T wave of the preceding beat. Proof that the premature P wave is unlike the normal P waves can be seen in lead V1, where the premature P wave begins with a downward deflection, unlike the normal P waves, which in this lead begin with an upward deflection. This tells you that in the premature systole, the atria were activated via an abnormal pathway.

3) The usual P-R interval is \(~0.10\) s, which is short (the normal P-R interval is between 0.12 and 0.20 s). The P-R interval preceding the premature QRS is longer than the usual P-R interval in this patient, most likely because of the shorter time that the AV node has had to recover from the preceding beat.

4) This is a premature atrial depolarization (PAD). The short P-R interval of the usual beats in Fig. 9, like that in Fig. 8, implies that the impulse transmitted from atria to ventricles has not encountered the normal delay, i.e., the impulse has not been slowed by passage through the AV node. Because the QRS in this patient does not begin with a delta wave, the impulse has crossed from the atria to the ventricles by a pathway that connects to the His-Purkinje system above the bifurcation of the bundle of His. This pattern has been attributed to a “bypass fiber of James” that connects the atrial myocardium to the AV bundle below the AV node; hence, ventricular activation is normal. As in WPW, this abnormal conducting pathway predisposes to reentrant paroxysmal supraventricular tachycardia; when the latter occurs in a patient with a short P-R interval, this is called the Lown-Ganong-Levine syndrome (LGL).

Case 3

Description. The basic rhythm is regular, but the 11th QRS is premature (Fig. 10). The answers to the following questions should help you to understand the mechanism for the premature systole.

Questions. 1) Is the contour of the premature QRS like the others in this record? What does this tell you about the mechanism responsible for this beat?

2) Is the premature QRS preceded by a P wave? What does this tell you about the mechanism responsible for this beat?
3) What type of premature systole is this?

4) Measure the interval between the two normal QRS complexes that “enclose” the premature QRS. Is this the same as the interval between two normal QRS complexes? What does this tell you about the effect of the premature systole on SA node depolarization? Note the pause following the premature systole. What is this called and how did this name come to be chosen?

5) Patients who experience a premature beat such as that shown in this record are usually unaware of the premature beat but feel an abnormally strong beat after the premature systole (called a postextrasystolic beat). Why is this so?

6) In Fig. 9, measure the two normal QRS complexes that “enclose” the premature systole. Is this the same as the interval between two normal QRS complexes? Why does this behavior differ from that associated with the premature systole in Fig. 10?

Answers to questions. 1) Because the premature QRS complex is abnormal, the ventricles have not been depolarized via the normal activation sequence. This implies that the impulse that initiated the premature QRS has arisen below the bifurcation of the bundle of His, i.e., from a site in one of the ventricles.

2) No. This implies that the impulse that initiated the premature QRS was not conducted into the ventricles from the atria.

3) This a premature ventricular depolarization (PVD).

4) The interval between the two normal QRS complexes that “enclose” the PVD is ~1.24 s, which is the same as the interval between two normal QRS complexes. This tells you that the premature beat has not “reset” the SA node pacemaker. The pause following the PVD has therefore occurred because the ventricles had to wait to be depolarized until the next impulse generated by the SA node was transmitted via the normal conducting pathway. This is called a “compensatory pause” because the delay has compensated for the prematurity of the PVD by allowing normal sinus control of the ventricles to resume after the pause.

5) There are two reasons why the postextrasystolic beat is usually stronger than normal. The first is that
the amount of blood ejected by the ventricles in this beat is greater than normal because the compensatory pause allows more blood to enter the ventricles (Starling’s Law of the Heart). The second reason is that contractility of the postextrasystolic beat is augmented by a mechanism called “postextrasystolic potentiation.” This is a manifestation of the Bowditch (positive) staircase, in which reopening of plasma membrane calcium channels by the premature beat allows a large calcium influx into the sarcoplasmic reticulum. This increases the intracellular calcium store available for release in the postextrasystolic beat.

6) The interval between the two normal QRS complexes that “enclose” the premature systole in Fig. 9 is significantly less than the interval between two normal QRS complexes because the atrial impulse that caused the PAD was conducted into and reset the SA node. The different timing of the first postextrasystolic beats in Figs. 9 and 10 is typical of that seen in premature atrial and ventricular depolarizations.

Case 4

Description. The abnormality in this ECG (Fig. 11) lies in the mechanism that has initiated the QRS complexes, which are normal in contour. The key to understanding the arrhythmia lies in your measurement of the P-R interval.

Questions. 1) What is the P-R interval (measure in lead II)? Is this normal? What does this tell you?

2) Estimate the mean P wave axis. Does atrial depolarization proceed in the normal direction, from superior to inferior? (Hint: Look at the direction of the P wave in lead aVF.)

3) What is likely to have initiated these P waves? What is the arrhythmia?

Answers to questions. 1) The P-R interval in lead II is 0.08 s, which is abnormally short. This tells us that the QRS complexes have not been initiated by an impulse that had first depolarized the atria and then were transmitted into the ventricles after encountering the normal delay in the AV node. Whereas this might be WPW, as in Fig. 8, the narrow QRS complex and absence of delta waves argues against this diagnosis. Instead, the normal QRS complexes indicate that the ventricles were depolarized via the normal conduction pathway.
2) The mean P wave vector is about −90° (the P waves are inverted in lead aVF), whereas the normal P wave is directed inferiorly and to the left, away from the SA node pacemaker. Because the wave of atrial depolarization in this patient is proceeding superiorly, rather than in the normal inferior direction, the atria have been depolarized abnormally, in a superior direction.

3) These P waves are likely to have originated in the AV junction. This explains both the short P-R interval and the “upside down” P waves, which are called “retrograde” P waves. This is therefore an example of a junctional rhythm.

**Questions.**

1) Are there P waves before the QRS complexes? What does this tell you? What is the QRS duration? What does this tell you?

2) Are there P waves anywhere in this record? (Hint: Look carefully at the limb leads.)

3) What is the arrhythmia?

4) Patients with the arrhythmia commonly have large jugular venous pulsations, called “cannon waves.” Can you explain why?

**Answers to questions.**

1) There are no P waves before the QRS complexes, which tells us that the ventricles were depolarized by a mechanism that does not involve prior depolarization of the atria. The normal QRS duration (~0.08 s) tells us that the right and left ventricles were depolarized synchronously (which is normal) by an impulse that arose above the bifurcation of the bundle of His.

2) On careful examination of the limb leads you will see notches on the S-T segments, immediately after
the QRS complexes. In leads II, III, and aVF, these can be seen to be inverted (retrograde) P waves.

3) This is another example of a junctional rhythm, but unlike Case 4, the retrograde P waves follow rather than precede the QRS complexes. These used to be called “upper” and “lower” nodal rhythms (Figs. 11 and 12, respectively) on the basis of the assumption that in the former (Fig. 11) an ectopic pacemaker in the upper AV node depolarized the atria before the ventricles, whereas in the latter (Fig. 12) a pacemaker in the lower AV node depolarized the ventricles ahead of the atria. These terms have fallen out of use with recognition that in junctional rhythms the speed of antegrade and retrograde conduction is more important than the location of the initiating event in determining the relative timing of P waves and QRS complexes. The ST-T abnormalities in this patient, which resemble those caused by digitalis, provide a clue to the underlying mechanism. This is because one of the arrhythmogenic effects of the cardiac glycosides is to accelerate spontaneous depolarization of pacemaker cells in the AV node. If this arrhythmia is not recognized and the digitalis dose not decreased, worsening digitalis toxicity can cause a rapid automatic supraventricular tachycardia and, in some patients, more dangerous—and potentially lethal—ventricular tachyarrhythmias.

4) Large jugular venous pulsations (called “cannon waves”) seen in this type of junctional rhythm were caused when the atria contracted after the tricuspid valve had been closed by the immediately preceding ventricular systole. Atrial systole against a closed AV valve converts the energy of atrial contraction into pressure, which gives rise to the cannon waves; normally, the energy released during atrial systole propels blood across the atrioventricular valves into the ventricles.

Case 6

Description. The key to understanding the mechanism responsible for the irregular ventricular rhythm in this tracing is the atrial rhythm (Fig. 13).

Questions. 1) Are there P waves in this record? Look at both the inferior leads (leads II, III, and aVF) and

FIG. 13.
Case 6: Atrial flutter, showing typical F waves.
lead V1. What are the manifestations of atrial depolarization?

2) What is the mechanism of the arrhythmia?

3) Why is the ventricular rhythm irregular?

**Answers to questions.** 1) Deflections caused by atrial depolarization are seen clearly in leads II, III, and aVF and in lead V1. Lead V1 shows apparently discrete electrical events arising from atrial depolarization. These occur at an interval of ~0.19 s (which corresponds to a rate of 316 beats/min); however, these are not P waves. This is apparent in leads II, III, and aVF, where the deflections caused by atrial depolarization resemble the teeth of a saw; these are called “F waves” (capital “F” stands for flutter). These are diagnostic of atrial flutter, in which atrial rates are typically very close to 300 min⁻¹.

2) Atrial flutter generally occurs when a single wave of depolarization (a “mother wave”) goes around and around the atria. Normally, it takes ~0.2 s for each circuit; hence, the usual flutter rate is ~300 beats/min. Slower flutter rates are seen in patients who are taking drugs that slow impulse conduction (e.g., antiarrhythmic agents) or who have fibrotic or dilated atria.

3) There are more F waves than QRS complexes, so this record shows AV dissociation. This failure of each atrial depolarization to initiate a QRS complex can also be referred to as AV block, but the term “block” should be reserved for cases in which impulse transmission between the atria and ventricles has failed because of a conduction abnormality in the AV node. In this case, the failure of most atrial depolarizations to be conducted into the ventricles is caused by the normal ability of the AV node to “filter” excessively rapid impulses. The ventricular rhythm is irregular because of the extent of AV dissociation varies from beat to beat, which changes the ratio between F waves and QRS complexes. Interestingly, the last 7 beats in this record occur at a fairly regular rate of ~79 beats/min, which means that these beats exhibit 4:1 AV dissociation (four F waves per QRS complex).

**Case 7**

**Description.** The ventricular rhythm in this patient is irregular (Fig. 14). The QRS complexes are narrow, but there are ST-T changes consistent with left ventricular hypertrophy and/or digitalis effect.

**Questions.** 1) Are there P waves in this record? If not, are there any manifestations of atrial depolarization in this ECG?

2) What is the mechanism of the arrhythmia?

3) Why is the ventricular rhythm irregular?

**Answers to questions.** 1) P waves, which are discrete manifestations of atrial depolarization, are not seen; instead, there are undulations of the baseline (clearest in lead V3), which are called “f waves” (lowercase “f” stands for fibrillation). The irregular atrial activity is caused by disorganization of the passage of impulses over the atria.

2) The f waves and irregular timing of the QRS complexes are diagnostic of atrial fibrillation.

3) The ventricular rhythm is irregular in part because of the irregular arrival of atrial impulses at the upper end of the AV node. However, the mechanism of the irregular ventricular beating is more complex than meets the eye. This is apparent when one compares the intervals between the undulations in lead V3, which average ~0.2 s, with the intervals between QRS complexes, which are generally much longer. In the rhythm strip that runs along the bottom of this tracing, for example, the interval between the third and fourth QRS complexes is almost 1.5 s. This discrepancy between the short intervals between f waves and the much longer intervals between QRS complexes results from a phenomenon called “concealed conduction.” Drawn on the next page is a “ladder” or “Lewis” diagram (named for Sir Thomas Lewis, who systematized electrocardiography early in this century) that shows a conjectural reconstruction of three ventricular beats labeled V1–V3, which corre-
spond to the second to fourth QRS complexes in the rhythm strip in Fig. 14.

The three QRS complexes (V1–V3) are postulated to have been generated by five irregularly occurring atrial impulses (A1–A5). Atrial impulses A1 and A2 are relatively far apart, which allows both to be conducted through the AV node, where they generate QRS complexes V1 and V2. However, impulses A3 and A4 occur so soon after the preceding atrial impulse that their passage through the AV node is blocked (short horizontal lines in diagram); as a result, neither A3 nor A4 is conducted across the AV node to generate a QRS complex. The later arrival of impulse A5 after impulse A4 allows the AV node sufficient time to recover from the latter, which enables A5 to generate the third QRS complex (V3). This behavior is called concealed conduction because we presume that the long pause in ventricular beating seen after V2 is caused by impulses (here called A3 and A4) that are conducted into, but do not cross, the AV node. Impulses A3 and A4, whose conduction into the AV node delays the appearance of the third QRS (V3), do not themselves initiate a QRS complex, so their conduction into the AV node is concealed.

Case 8

Description. The ventricular rhythm in this tracing (Fig. 15) is regular and very slow, at a rate of ~30 beats/min. The QRS complexes are widened (~0.11 s in lead II).

Questions. 1) What is the rate of the P waves in this record?

2) Do these P waves bear any relationship to the QRS complexes?

3) At what site are the QRS complexes being generated? Can this explain their duration?
4) What is this arrhythmia called?

**Answers to questions.** 1) The P waves occur regularly at a rate of ~75 beats/min.

2) The P waves bear no relationship to the QRS complexes; there is neither a fixed P-R interval nor any pattern relating P waves to QRS complexes. In fact, atrial and ventricular beating are entirely independent of each other, which means that there is no electrical connection between atria and ventricles.

3) The fact that the QRS complexes in this record are widened indicates that they have arisen below the bifurcation of the bundle of His. Their slow rate is consistent with a “lower” pacemaker in the His-Purkinje system of one of the ventricles, so these are idioventricular beats.

4) This behavior is diagnostic of third-degree (complete) AV block in which atrial and ventricular contraction are independent of each other.

**Case 9**

**Description.** The ventricular rhythm in this tracing (Fig. 16) is irregular, but the P waves (which are abnormally broad) are regular. The QRS complexes are ~0.11 s in duration, which with the rSR' configuration in lead V1 is diagnostic of incomplete right bundle branch block (this would have been complete right bundle branch block if the QRS duration had been 0.12 s or longer). The ST segment depressions and inverted T waves in leads V4–V6 are abnormal and are consistent with left ventricular hypertrophy, ischemia, or both.

**Questions.** 1) What is the relationship between the P waves and the QRS complexes in this record? This is best evaluated in the rhythm strip at the bottom, where you should begin after the pause that follows the fourth QRS. (Note that a P wave is superimposed on the T wave of this beat.) Continue by measuring the P-R intervals of the succeeding beats.

2) Note that the interval between the fifth and eighth QRS complexes in the rhythm strip shortens progressively. Can you explain the basis for this subtle increase in the rate of ventricular beating, which is called “group beating”?

3) What is this arrhythmia called? What is the most likely underlying mechanism?
Answers to questions. 1) The P-R intervals in this record are not constant, and not all P waves are followed by a QRS complex. There is a pattern, however, in the timing between the P waves and QRS complexes. If you begin with the P wave that follows the fourth QRS in the rhythm strip, this relationship is apparent in the following diagram, in which the left-hand QRS corresponds to the fourth QRS on the rhythm strip. (labeled R-R intervals in the diagram) reflects the fact that although the P-R interval increases progressively, the increase occurs by the addition of decreasing increments. As a result, the R-R interval shortens between successive QRS complexes; this is the pattern called “group beating,” which is typical of the Wenckebach phenomenon.

2) Progressive shortening of the intervals between the fifth and eighth QRS complexes in the rhythm strip Note the progressive prolongation of P-R interval that ends with a “dropped beat,” in which the P wave is completely blocked. This behavior is called the Wenckebach phenomenon.

3) This arrhythmia represents Mobitz type I second-degree AV block. The progressive lengthening of the P-R interval before the “dropped” beat implies that this is a physiological block of impulse conduction in the region of calcium channel-dependent conduction in the AV node that culminates in complete failure of conduction (the blocked P waves). The long pause
that follows the completely blocked P wave allows these channels to recover, which accounts for the shortened P-R interval of the first cycle after the dropped beat.

Case 10

Description. This tracing (Fig. 17) shows a continuous lead II in which four sinus beats are followed by a grossly disorganized ventricular rhythm. The Q-T interval of the sinus beats is ~0.46 s, which for the sinus rate of ~80 min⁻¹ is prolonged.

Questions. 1) What is the nature of the disorganized rhythm?

2) How does the disorganized rhythm begin? Does this tell you anything about the cause?

Answers to questions. 1) The “twisting” of the ventricular complexes around the isoelectric line when the disorganized rhythm begins is called “torsades de pointes,” a special type of ventricular tachycardia most often seen in patients with prolonged Q-T intervals. Torsades can be caused by drugs, hypocalcemia, hypokalemia, and heritable molecular abnormalities involving cardiac ion channels. As the record continues, the pattern begins to break down to a chaotic rhythm that probably represents ventricular fibrillation, in which organized contraction of the ventricle ceases and the heart can no longer pump (cardiac arrest).

2) The episode of torsades begins after a premature QRS complex (the 4th in this rhythm strip) has fallen on the T wave of the preceding QRS (the latter represents the “vulnerable” period). This is the “R on T” phenomenon, in which an impulse that reaches the ventricles during the vulnerable period finds some regions in a partially depolarized state and can initiate a slowly conducted wave of depolarization that leads to a reentrant arrhythmia.

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