Pacemaker Timing Cycles

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Understanding various pacing modes and paced electrocardiograms (ECGs) requires a thorough understanding of pacemaker timing cycles. Pacemaker timing cycles include all potential variations of a single complete pacing cycle—the time from paced ventricular beat to paced ventricular beat; the time from paced ventricular beat to an intrinsic ventricular beat, whether it is a conducted R wave or a premature ventricular contraction (PVC); the time from paced atrial beat to paced atrial beat; the time from intrinsic atrial beat to paced atrial beat; the time from intrinsic ventricular beat to paced ventricular beat; and so forth. These cycles include events sensed, events paced, and periods when the sensing circuit or circuits are refractory. Each portion of the pacemaker timing cycle should be considered in milliseconds and not in pulses per minute (ppm). Although thinking of the patient's pacing rate in paced beats per minute may be easier, portions of the timing cycle are too brief to consider in any unit but milliseconds.

Knowledge of the relation between elements of the paced ECG enhances understanding of pacemaker rhythms. Although multiple unknown factors may affect a native rhythm, each timing circuit of a pacemaker can function in only one of two states. A given timer can proceed until it completes its cycle; completion results in either the release of a pacing stimulus or the initiation of another timing cycle. Alternatively, a given timer can be reset, at which point it starts the timing period again.

To make this chapter more readable and to facilitate clarity, a series of abbreviations is used to designate native and paced events and portions of the timing cycle. These abbreviations are listed in Box 6.1. P indicates native atrial depolarization, A an atrial paced event, R native ventricular depolarization, and V a ventricular paced event. I represents an interval. From this, PR refers to a native complex that completely inhibits the pacemaker on both the atrial and the ventricular channels. AV refers to pacing sequentially in both the atrium and the ventricle. If an atrial paced complex is followed by native ventricular depolarization that inhibits the ventricular output of the pacemaker, the designation is AR. If a native atrial complex is followed by a paced ventricular depolariza-

Box 6.1. Abbreviations for Native and Paced Events and Portions of the Timing Cycle

P	Native atrial depolarization
A	Atrial paced event
R	Native ventricular depolarization
V	Ventricular paced event
I	Interval
AV	Sequential pacing in the atrium and ventricle
AVI	Programmed atrioventricular pacing interval
AR	Atrial paced event followed by intrinsic ventricular depolarization
ARP	Atrial refractory period
PV	Native atrial depolarization followed by a paced ventricular event, P-synchronous pacing
AEI	Interval from a ventricular sensed or paced event to an atrial paced event, the VA interval
LRL	Lower rate limit
URL	Upper rate limit
MTR	Maximum tracking rate
MSR	Maximum sensor rate
PVARP	Postventricular atrial refractory period
RRAVD	Rate-responsive atrioventricular delay
VA	Ventriculoatrial interval: interval from a sensed or paced ventricular event to an atrial paced event
VRP	Ventricular refractory period

tion, P-synchronous pacing, the designation is PV. Because the pacemaker timing cycle in dual-chamber pacing has more portions to consider than single-chamber pacing, more discussion is devoted to understanding dual-chamber timing cycles, specifically those of universal (DDD) pacing systems.

Multiple programmable features may affect device behavior (Box 6.2). These are discussed throughout the chapter.

PACING NOMENCLATURE

A three-letter code describing the basic function of the various pacing systems was first proposed in 1974 by a combined task force from the American Heart Association and the American College of Cardiology. Since then, the code has been updated periodically.[1] It is a generic code and, as such, does not describe specific or unique functional characteristics of each device. The code has five positions.

The first position reflects the chamber or chambers in which stimulation occurs. A refers to the atrium, V indicates the ventricle, and D means dual chamber, or both atrium and ventricle.

The second position refers to the chamber or chambers in which sensing occurs. The letter designators are the same as those for the first position. Man-

Box 6.2. Features That May Affect Device Behavior*

Intrinsic rate *slower* than programmed base rate
- Hysteresis
- Sleep or rest rate
- Special algorithms (+PVARP on PVC)

Base rate (AV, AR) *higher* than programmed base rate
- Sensor driven
- Rate smoothing
- Mode-switching response rate
- Special algorithms (+PVARP on PVC)

Intrinsic AV conduction interval (PR, AR) *longer* than programmed paced or sensed AVI
- AV or PV hysteresis
- Sinus rate with intact AV conduction exceeding MTR

Paced or sensed AVI *shorter* than programmed paced or sensed AVI
- Rate-responsive AV delay
- Negative AV or PV hysteresis
- Safety pacing
- NCAP (noncompetitive atrial pacing)
- Auto-threshold test

Loss of atrial tracking (DDD mode)
- Automatic mode switch
- MSR > MTR

* Not necessarily continuously; the effect can be on single cycles or during a brief period.

ufacturers also use S in both the first and the second positions to indicate that the device is capable of pacing only a single cardiac chamber. Once the device is implanted and connected to a lead in either the atrium or the ventricle, S should be changed to either A or V in the clinical record to reflect the chamber in which pacing and sensing are occurring.

The third position refers to the mode of sensing, or how the pacemaker responds to a sensed event. An I indicates that a sensed event inhibits the output pulse and causes the pacemaker to recycle for one or more timing cycles. T means that an output pulse is triggered in response to a sensed event. D, in a manner similar to that in the first two positions, means that there are dual modes of response. This designation is restricted to dual-chamber systems. An event sensed in the atrium inhibits atrial output but triggers ventricular output. Unlike the single-chamber triggered mode, in which an output pulse is triggered immediately on sensing, a delay occurs between the sensed atrial event and the triggered ventricular output to mimic the normal PR interval. If a native ventricular signal or R wave is sensed, it inhibits ventricular output and possibly even atrial output, depending on where sensing occurs.

The fourth position of the code reflects rate modulation. An R in the fourth position indicates that the pacemaker incorporates a sensor to control the rate independently of intrinsic electrical activity of the heart.

The fifth position indicates whether multisite pacing is not present (O) or present in the atrium (A), ventricle (V), or both (D). Multisite pacing is defined for this purpose as stimulation sites in both atria, both ventricles, more than one stimulation site in any single chamber, or any combination of these.

PACING MODES

Ventricular Asynchronous Pacing, Atrial Asynchronous Pacing, and AV Sequential Asynchronous Pacing

Ventricular asynchronous (VOO) pacing is the simplest of all pacing modes because there is neither sensing nor mode of response. The timing cycle is shown in Figure 6.1. Irrespective of any other events, the ventricular pacing artifacts occur at the programmed rate. The timing cycle cannot be reset by any intrinsic event. In the absence of sensing, there is no defined refractory period.

Atrial asynchronous (AOO) pacing behaves exactly like VOO, but the pacing artifacts occur in the atrial chamber.

Dual-chamber, or AV sequential asynchronous (DOO), pacing has an equally simple timing cycle. The interval from atrial artifact to ventricular artifact (atrioventricular interval, AVI) and the interval from the ventricular artifact to the subsequent atrial pacing artifact (ventriculoatrial interval, VAI, or atrial escape interval, AEI) are both fixed. The intervals never change, because the pacing mode is insensitive to any atrial or ventricular activity, and the timers are never reset (Fig. 6.2).

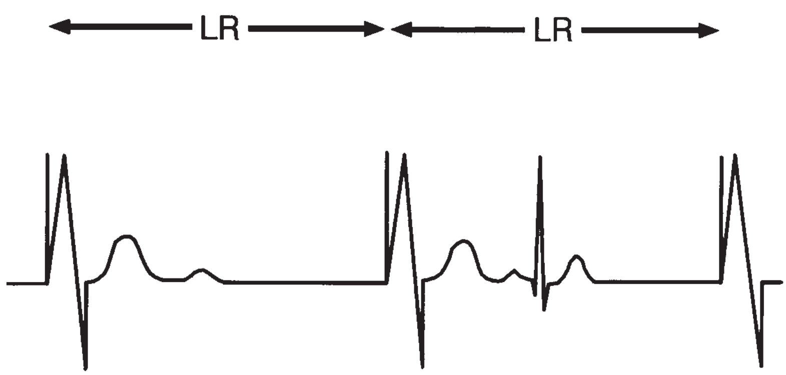


Figure 6.1. The VOO timing cycle consists of only a defined rate. The pacemaker delivers a ventricular pacing artifact at the defined rate regardless of intrinsic events. In this example, an intrinsic QRS complex occurs after the second paced complex, but because there is no sensing in the VOO mode, the interval between the second and the third paced complex remains stable.

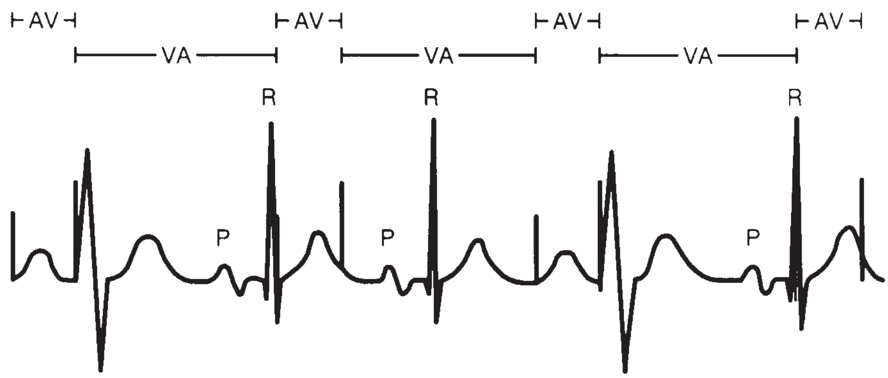


Figure 6.2. The DOO timing cycle consists of only defined AV and VV intervals. The VAI is a function of the AV and VV intervals. An atrial pacing artifact is delivered, and the ventricular artifact follows at the programmed AVI. The next atrial pacing artifact is delivered at the completion of the VAI. The intervals do not vary because no activity is sensed; that is, nothing interrupts or resets the programmed cycles.

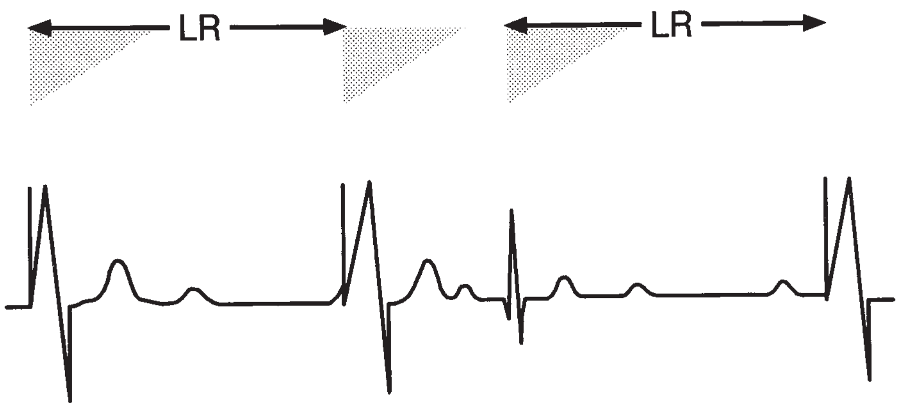


Figure 6.3. The VVI timing cycle consists of a defined LRL and a VRP *(shaded triangles)*. When the LRL timer is complete, a pacing artifact is delivered in the absence of a sensed intrinsic ventricular event. If an intrinsic QRS occurs, the LRL timer is started from that point. A VRP begins with any sensed or paced ventricular activity.

Ventricular Inhibited Pacing

By definition, ventricular demand inhibited (VVI) pacing incorporates sensing on the ventricular channel, and pacemaker output is inhibited by a sensed ventricular event (Fig. 6.3). VVI pacemakers are refractory after a paced or sensed ventricular event, a period known as the ventricular refractory period (VRP). Any ventricular event occurring within the VRP is not sensed and does not reset the ventricular timer (Fig. 6.4).

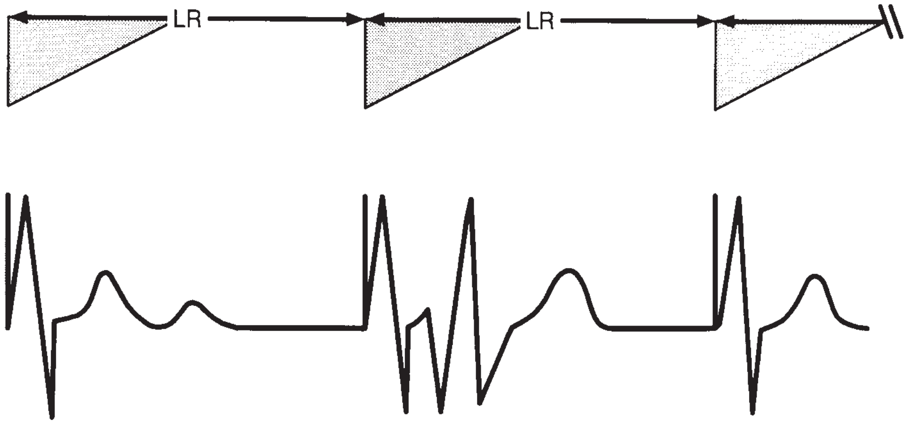


Figure 6.4. If, in the VVI mode, a ventricular event occurs during the VRP *(shaded triangles)*, it is not sensed and therefore does not reset the LRL timer.

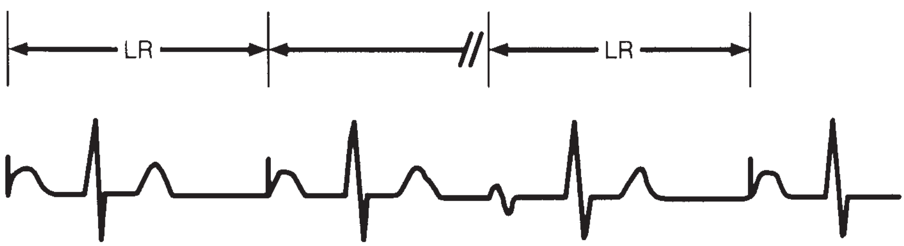


Figure 6.5. The AAI timing cycle consists of a defined LRL and an ARP. When the LRL timer is complete, a pacing artifact is delivered in the atrium in the absence of a sensed atrial event. If an intrinsic P wave occurs, the LRL timer is started from that point. An ARP begins with any sensed or paced atrial activity.

Atrial Inhibited Pacing

Atrial inhibited (AAI) pacing, the atrial counterpart of VVI pacing, incorporates the same timing cycles, with the obvious differences that pacing and sensing occur from the atrium and pacemaker output is inhibited by a sensed atrial event (Fig. 6.5). An atrial paced or sensed event initiates a refractory period during which the pacemaker senses nothing. Confusion can arise when multiple ventricular events occur during atrial pacing. For example, a premature ventricular beat following the intrinsic QRS that occurs in response to the paced atrial beat does not inhibit an atrial pacing artifact from being delivered (Fig. 6.6). When the AA timing cycle ends, the atrial pacing artifact is delivered regardless of ventricular events, because an AAI pacemaker should not sense anything in the ventricle. The single exception to this rule is far-field sensing; that is, the ventricular signal is large enough to be inappropriately sensed by the

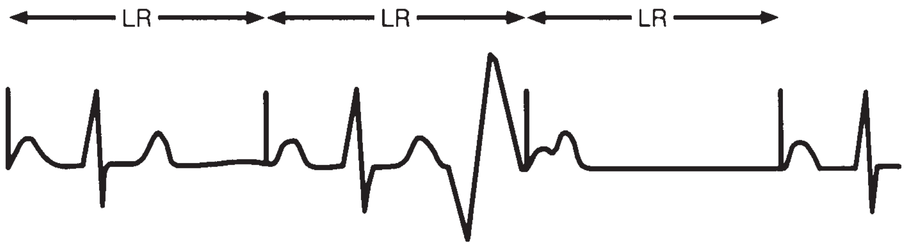


Figure 6.6. In the AAI mode, only atrial activity is sensed. In this example, it may appear unusual for paced atrial activity to occur so soon after intrinsic ventricular activity. Because sensing occurs only in the atrium, ventricular activity would not be expected to reset the pacemaker's timing cycle.

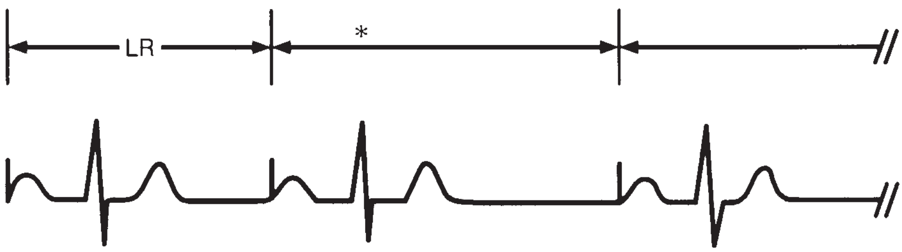


Figure 6.7. In this example of AAI pacing, the AA interval is 1000 milliseconds (60 ppm). The interval between the second and third paced atrial events is greater than 1000 milliseconds. The interval from the second QRS complex to the subsequent atrial pacing artifact is 1000 milliseconds. This occurs because the second QRS complex *(asterisk)* has been sensed on the atrial lead (far-field sensing) and has inappropriately reset the timing cycle. LR = lower rate.

atrial lead (Fig. 6.7). In this situation, the atrial timing cycle is reset. Sometimes this anomaly can be corrected either by making the atrial channel less sensitive or by lengthening the refractory period.

Single-Chamber Triggered-Mode Pacing

In single-chamber triggered-mode pacing, the pacemaker releases an output pulse every time a native event is sensed. This feature increases the current drain on the battery, accelerating its rate of depletion. This mode of pacing also deforms the native signal, compromising ECG interpretation. However, it can serve as an excellent marker for the site of sensing within a complex. It can also prevent inappropriate inhibition from oversensing when the patient does not have a stable native escape rhythm. In addition, it can be used for noninvasive electrophysiologic studies, with the already implanted pacemaker tracking chest wall stimuli created by a programmable stimulator. One special requirement to use the triggered mode for noninvasive electrophysiologic studies is shortening the refractory period intentionally, thereby allowing the implanted pacemaker to track external chest wall stimuli to rapid rates and close coupling intervals.

Rate-Modulated Pacing

The "sensor function of the pacemaker" refers to modulation of the paced rate in response to an input signal other than the presence or absence of native depolarization. The most widely used sensors include those that sense motion, either acceleration or vibration, impedance signals that measure minute ventilation and the measured interval from pacemaker stimulus to the T wave, i.e., a QT-interval sensor. Many other sensors have been used but not widely.

Single-Chamber Rate-Modulated Pacing: Single-chamber pacemakers capable of rate-modulated (SSIR) pacing can be implanted in the ventricle (VVIR) or atrium (AAIR). The timing cycles for SSIR pacemakers are not markedly different from those of their non–rate-modulated counterparts. The timing cycle includes the basic VV or AA interval and a refractory period from the paced or sensed event. The difference lies in the variability of the VV or AA interval (Fig. 6.8). Depending on the sensor incorporated and the patient's level of exertion,

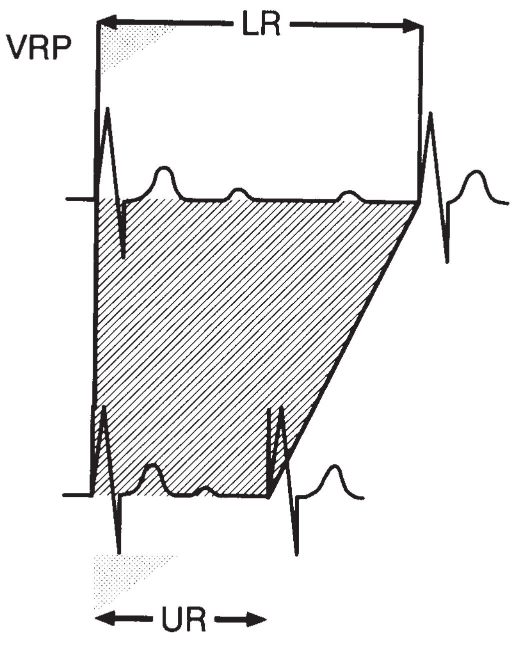


Figure 6.8. The VVIR timing cycle consists of an LRL, an upper rate limit (UR), and a VRP, represented by shaded triangles. As indicated by sensor activity, the VV cycle length shortens accordingly. (The *striped area* represents the range of sensor-driven VV cycle lengths.) In most VVIR pacemakers, the VRP remains fixed despite the changing VV cycle length. In selected VVIR pacemakers, the VRP shortens as the cycle length shortens.

the basic interval is shorter than the programmed lower rate limit (LRL). Shortening requires that an upper rate limit (URL) be programmed to define the absolute shortest cycle length allowable. Most approved SSIR pacemakers incorporate a fixed refractory period; that is, regardless of whether the pacemaker is operating at the LRL or URL, the refractory period remains the same. Thus, at the higher rates under sensor drive, the pacemaker may effectively become SOOR, because the alert period during which sensing can occur is so abbreviated. Native beats falling during the refractory period are not sensed. Hence, in SSIR pacing systems, if the refractory period is programmable, it should be programmed to a short interval to maximize the sensing period at both the low and the high sensor-controlled rates. In some pacemakers, when the cycle length shortens, the refractory period shortens correspondingly; this is referred to as the *rate-variable refractory* period. This event is analogous to the QT interval of the native ventricular depolarization.

Single-Chamber and Dual-Chamber Rate-Modulated Asynchronous Pacing: The asynchronous pacing modes (that is, AOO, VOO, and DOO, as explained previously) have fixed intervals that are insensitive to all intrinsic events and have timers that are never reset. If rate modulation is incorporated in an asynchronous pacing mode, the basic cycle length is altered by sensor activity. In the single-chamber rate-modulated asynchronous (AOOR and VOOR) pacing modes, any alteration in cycle length is attributable to sensor activity and not to the sensing of intrinsic cardiac depolarizations. In the dual-chamber rate-modulated asynchronous (DOOR) pacing mode, the pacing rate changes in response to the sensor input signal but not to the native P or R wave. In some pacemakers, the AVI may be programmed to shorten progressively as the rate increases, whereas in other units, it remains fixed at the initial programmed setting.

Atrioventricular Sequential, Ventricular Inhibited Pacing

AV sequential, ventricular inhibited (DVI) pacing is rarely used. However, this pacing mode is a programmable option in most available dual-chamber pacemakers. For this reason, it is important to understand the timing cycles for DVI pacing.[2,3]

By definition, DVI provides pacing in both the atrium and the ventricle (D) but sensing only in the ventricle (V). The pacemaker is inhibited and reset by sensed ventricular activity but ignores all intrinsic atrial complexes. The DVI units in the first generation were large and bulky and had two relatively large bipolar leads. The bipolar design produced small output pulses and generated a highly localized sensing field. In this setting, the ventricular sense amplifier remained alert when the atrial stimulus was released and throughout the AVI. Thus, a native R wave during the AVI was sensed so that ventricular output was inhibited and the AEI was reset (Fig. 6.9A). For both atrial and ventricular stimuli to be inhibited, the sensed R wave must occur during the AEI.

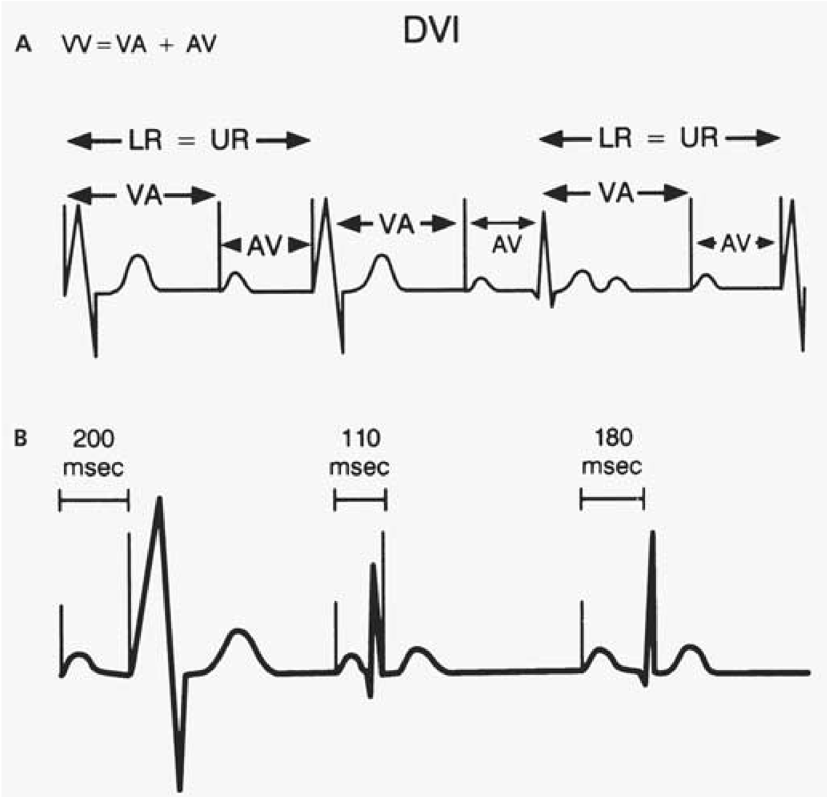


Figure 6.9. **A:** In the noncommitted version of DVI, the components of the timing cycle are the same as those for DVIC (see Fig. 6.10). However, if ventricular activity is sensed after the atrial pacing artifact, ventricular output is inhibited; that is, a ventricular pacing artifact is not committed to the previous atrial pacing artifact. **B:** In the modified or partially committed version of DVI, ventricular events sensed within the nonphysiologic AVI do not inhibit ventricular output, and a ventricular pacing stimulus occurs at the end of the interval. Ventricular events occurring within the physiologic AVI inhibit pacemaker function. In this example, the first paced atrial and ventricular events represent normal DVI pacing. The second paced atrial and intrinsic ventricular complex demonstrates a spontaneous ventricular event occurring within the nonphysiologic AVI and resulting in a ventricular pacing stimulus. In the third event shown, after an atrial paced event, a spontaneous ventricular event falls within the physiologic AVI, resulting in inhibition of ventricular pacing function.

Improvements in circuit design enabled the manufacturers to reduce the size of the pulse generator. They also made the next generation unipolar to facilitate venous access for the two leads. The large unipolar atrial stimulus could be sensed on the ventricular channel. It would be sensed by the pacemaker as a ventricular event and inhibit ventricular output. This occurrence is known as *crosstalk*, which is potentially catastrophic if concomitant AV block is present. To prevent crosstalk, the second generation of DVI pacemakers initiated the VRP on completion of the AEI timer. Thus, once an atrial output pulse occurred, the ventricular sense amplifier was refractory, and the pacemaker was obligated to release a ventricular output pulse, regardless of whether it was physiologically necessary. This event was termed *committed AV sequential pacing* (Fig. 6.10). It caused significant confusion because a normally functioning system might demonstrate functional undersensing and functional noncapture in both atrium and ventricle simultaneously.

The present generation of devices still requires a period of ventricular refractoriness, a "ventricular blanking period," to minimize the chance of crosstalk, but this interval is brief, lasting from 12 to 125 milliseconds. In many pacemakers the duration of this interval is programmable. If the atrial stimulus were to coincide with a native R wave, for example, a PVC, and the intrinsic deflection of the native complex fell outside the blanking period, the R wave would be sensed, and ventricular output would be inhibited. In this situation, the pacemaker would behave like the earlier noncommitted systems. If, however, the intrinsic deflection coincided with the blanking period, the R wave would not be seen, and the pacemaker would release a ventricular output pulse at the end of the AVI in a manner analogous to that of the committed systems. This operation has been termed *modified* or *partially committe*d to reflect the fact that the devices may demonstrate both noncommitted and committed functions as part of their normal behavior[4] (Fig. 6.9B).

The timing cycle (VV) consists of the AVI and VAI. The basic cycle length (VV), or LRL, is programmable, as is the AVI. The difference, VV–AV, is the VAI,

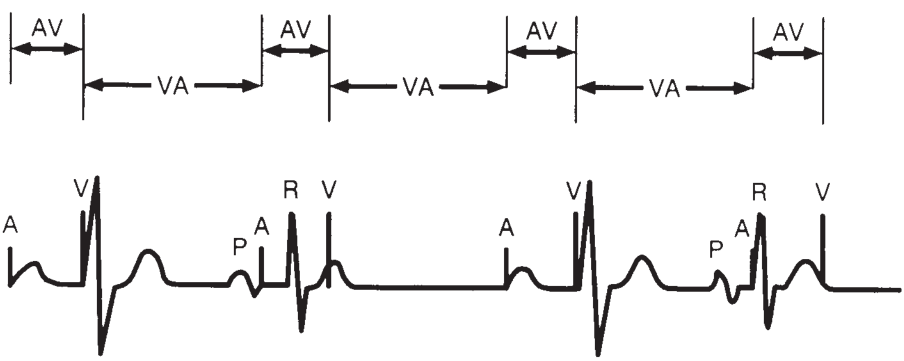


Figure 6.10. The timing cycle in committed DVI consists of an LRL, an AVI, and a VRP. The VRP is initiated with any sensed or paced ventricular activity. (By definition, there is no atrial sensing and, therefore, no defined ARP.) The VAI is equal to the VV or LRL interval minus the AVI. In a committed system, a ventricular pacing artifact follows an atrial pacing artifact at the AVI regardless of whether intrinsic ventricular activity has occurred. In this example, the LRL is 1000 milliseconds, or 60 ppm, and the AVI is 200 milliseconds. At the end of the VAI, 800 milliseconds after a ventricular event, if no ventricular activity has been sensed, the atrial pacing artifact is delivered. A ventricular pacing artifact occurs 200 milliseconds later, irrespective of any intrinsic events. This is functional undersensing, because the ventricular pacing artifact is delivered as a function of the DVI pacing mode.

or AEI. During the initial portion of the VAI, the sensing channel is refractory. (The refractory period is almost always a programmable interval.) After the refractory period, the ventricular sensing channel is again operational, or "alert." If ventricular activity is not sensed by the expiration of the VAI, atrial pacing occurs, followed by the AVI. If intrinsic ventricular activity occurs before the VAI is completed, the timing cycle is reset. (Additional discussion of crosstalk, the ventricular blanking period, and ventricular safety pacing can be found in the section that specifically discusses AVI.)

Atrioventricular Sequential, Non–P-Synchronous Pacing with Dual-Chamber Sensing: AV sequential pacing with dual-chamber sensing, non–P-synchronous (DDI) pacing can be thought of as either an upgrade of DVI noncommitted pacing or a downgrade of DDD pacing—that is, DDD pacing without atrial tracking.[5] The difference between DVI and DDI is that DDI incorporates atrial sensing as well as ventricular sensing. This prevents competitive atrial pacing that can occur with DVI pacing. The DDI mode of response is inhibition only; that is, no tracking of P waves can occur. Therefore, the paced ventricular rate cannot be greater than the programmed LRL. The timing cycle consists of the LRL, AVI, postventricular atrial refractory period (PVARP), and VRP. The PVARP is the period after a sensed or paced ventricular event during which the atrial sensing circuit is refractory. The atrial sensing circuit does not sense any atrial event occurring during the PVARP. If a P wave occurs after the PVARP and is sensed, no atrial pacing artifact is delivered at the end of the VAI. The subsequent ventricular pacing artifact cannot occur until the VV interval has been completed; that is, the LRL cannot be violated (Fig. 6.11).

It bears repeating that, because P-wave tracking does not occur with the DDI mode, the paced rate is never greater than the programmed LRL. A slight exception to this statement may occur when an intrinsic ventricular complex takes place after the paced atrial beat (AR) and inhibits paced ventricular output before completion of the programmed AVI; that is, AR is less than AV. In this situation, the cycle length from A to A is shorter than the programmed LRL by the difference between the AR and the AVI (Fig. 6.12).

Atrioventricular Sequential, Non–P-Synchronous, Rate-Modulated Pacing with Dual-Chamber Sensing

The timing cycles for non–P-synchronous, rate-modulated AV sequential (DDIR) pacing are the same as those described previously for DDI pacing except that paced rates can exceed the programmed LRL through sensor-driven activity. Depending on the sensor incorporated and the level of exertion of the patient, the basic cycle length shortens from the programmed LRL. This cycle length change requires that a URL be programmed to define the absolute shortest cycle length allowable.

Even though no P-wave tracking occurs in a DDIR system, an intrinsic P wave may inhibit the atrial pacing artifact and give the appearance of P-wave

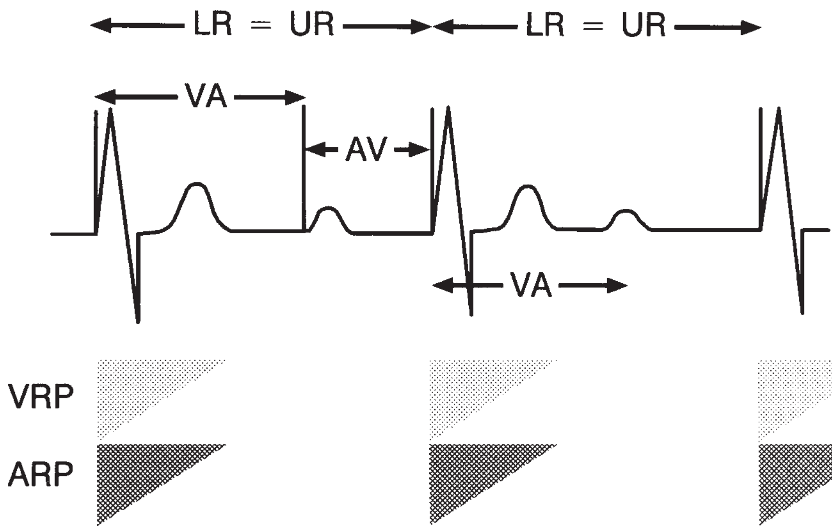


Figure 6.11. The timing cycle in DDI consists of an LRL, an AVI, a VRP, and an ARP. The VRP is initiated by any sensed or paced ventricular activity, and the ARP is initiated by any sensed or paced atrial activity. DDI can be thought of as DDD pacing without the capability of P-wave tracking or DVI without the potential for atrial competition by virtue of atrial sensing. The LRL cannot be violated even if the sinus rate is occurring at a faster rate. For example, the LRL is 1000 milliseconds, or 60 ppm, and the AVI is 200 milliseconds. If a P wave occurs 500 milliseconds after a paced ventricular complex, the AVI is initiated; but at the end of the AVI, 700 milliseconds from the previous paced ventricular activity, a ventricular pacing artifact cannot be delivered, because it would violate the LRL.

tracking if an appropriately timed intrinsic atrial depolarization falls within the atrial sensing window (ASW).[6] This phenomenon is coincidental.

In a DDDR pacing system in which the programmed maximum sensor rate (MSR) is greater than the maximum tracking rate (MTR), AV sequential pacing occurs when the sensor function drives the ventricular rate above the programmed maximum rate. The actual mode at this time is DDIR. If the intrinsic atrial rate also exceeds the MTR so that the native atrial signal is sensed, atrial output is inhibited. Meanwhile, the ventricular paced complex is controlled by the sensor. The appearance may be of PV pacing (atrial-sensed ventricular pacing), with the ventricular rate violating the MTR. In actuality, the ventricular paced complex is a result of sensor drive, and if the sensor input to the pacemaker would not allow a paced rate this rapid, the ventricular rate would be limited by the MTR limit.

Atrial Synchronous (P-Tracking) Pacing: Atrial synchronous (P-tracking) (VDD) pacemakers pace only in the ventricle (V), sense in both atrium and ventricle (D), and respond both by inhibition of ventricular output by intrinsic ventricular activity (I) and by ventricular tracking of P waves (T). This mode of pacing

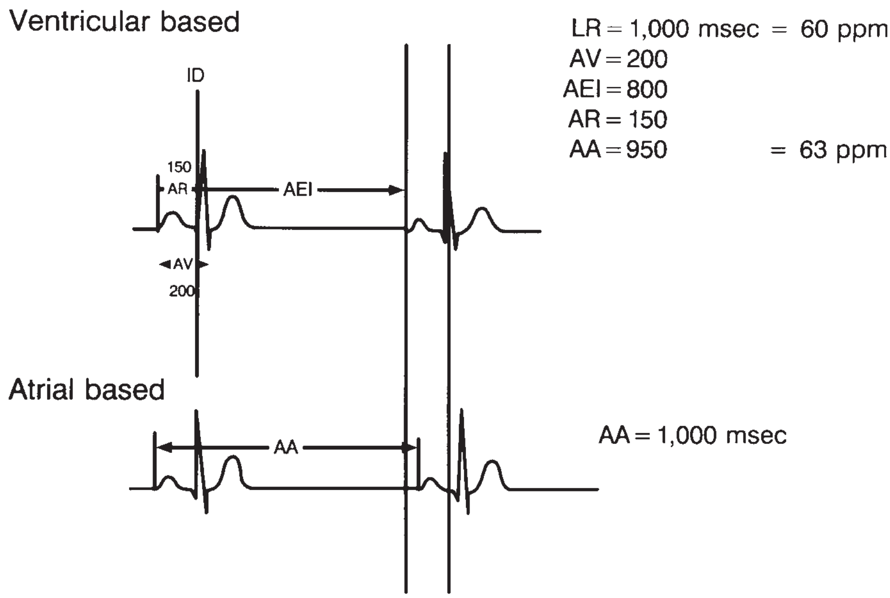


Figure 6.12. **Top:** With ventricular-based timing in patients with intact AV nodal conduction after AR pacing, the sensed R wave resets the AEI. The base pacing interval consists of the sum of the AR and the AEI; thus, it is shorter than the programmed minimum rate interval. **Bottom:** With atrial-based timing in patients with intact AV nodal conduction after AR pacing, the sensed R wave inhibits ventricular output but does not reset the basic timing of the pacemaker. There is atrial pacing at the programmed base rate. (From Levine PA, Hayes DL, Wilkoff BL, Ohman AE. Electrocardiography of rate-modulated pacemaker rhythms. Sylmar, CA: Siemens-Pacesetter, 1990. By permission of Siemens-Pacesetter.)

is a programmable option in many dual-chamber pacemakers.[7] The VDD mode is also available as a single-lead pacing system. In this system, a single lead is capable of pacing in the ventricle in response to sensing atrial activity by way of a remote electrode(s) situated on the intra-atrial portion of the ventricular pacing lead.

The timing cycle is composed of LRL, AVI, PVARP, VRP, and URL. A sensed atrial event initiates the AVI. If an intrinsic ventricular event occurs before termination of the AVI, ventricular output is inhibited, and the LRL timing cycle is reset. If a paced ventricular beat occurs at the end of the AVI, this beat resets the LRL. If no atrial event occurs, the pacemaker escapes with a paced ventricular event at the LRL; that is, the pacemaker displays VVI activity in the absence of a sensed atrial event (Fig. 6.13).

Dual-Chamber Pacing and Sensing with Inhibition and Tracking

Although the DDD timing cycle involves more intervals, standard dual-chamber pacing and sensing with inhibition and tracking (DDD) are reasonably easy to comprehend on the basis of the timing cycles already discussed.[7–12] The basic

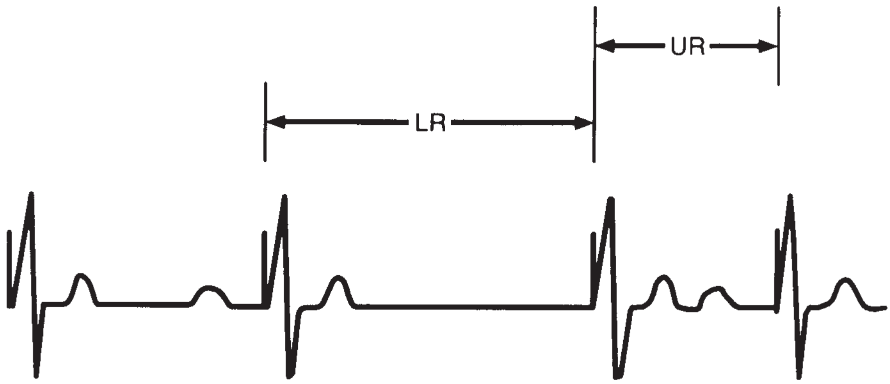


Figure 6.13. The timing cycle of VDD consists of an LRL, an AVI, a VRP, a PVARP, and a URL. A sensed P wave initiates the AVI (during the AVI, the atrial sensing channel is refractory). At the end of the AVI, a ventricular pacing artifact is delivered if no intrinsic ventricular activity has been sensed, that is, P-wave tracking. Ventricular activity, paced or sensed, initiates the PVARP and the VAI (the LRL interval minus the AVI). If no P-wave activity occurs, the pacemaker escapes with a ventricular pacing artifact at the LRL.

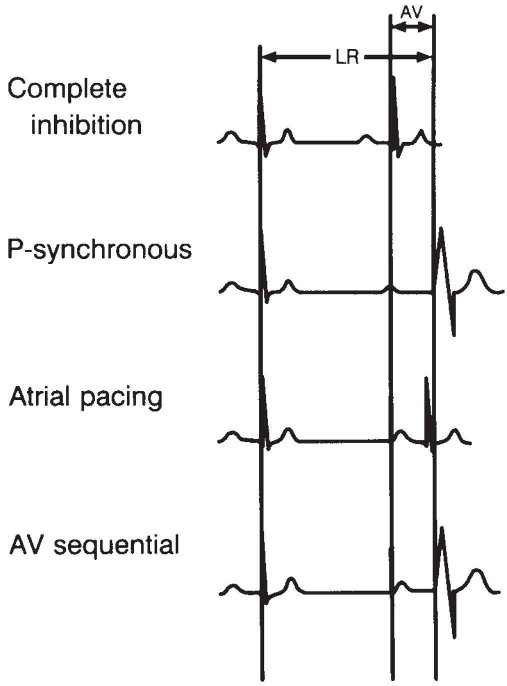
timing circuit associated with LRL pacing is divided into two sections. The first is the interval from a ventricular sensed or paced event to an atrial paced event and is known as the AEI, or VAI. The second interval begins with an atrial sensed or paced event and extends to a ventricular event. This interval may be defined by a paced AV, PR, AR, or PV interval. An atrial sensed event that occurs before completion of the AEI promptly terminates this interval and initiates an AVI, and the result is P-wave synchronous ventricular pacing.[8] If the intrinsic sinus rate is less than the programmed LRL, AV sequential pacing at the programmed rate or functional single-chamber atrial (AR) pacing occurs (Fig. 6.14A).

An option for "circadian response," or "sleep rate," in many contemporary pacemakers[1] allows a lower rate to be programmed for the approximate time during which the patient is sleeping. A separate, potentially faster LRL may then be programmed for waking hours. (For example, the LRL during waking hours may be programmed to 70 bpm, and the LRL during sleeping hours may be programmed to 50 bpm.) In some pacemakers, this feature is tied to a clock, and the usual waking and sleeping hours are programmed into the pacemaker. In other pacemakers, the sleep rate is also set on the basis of waking and sleeping hours, but verification by a sensor is required to allow rate changes to occur.

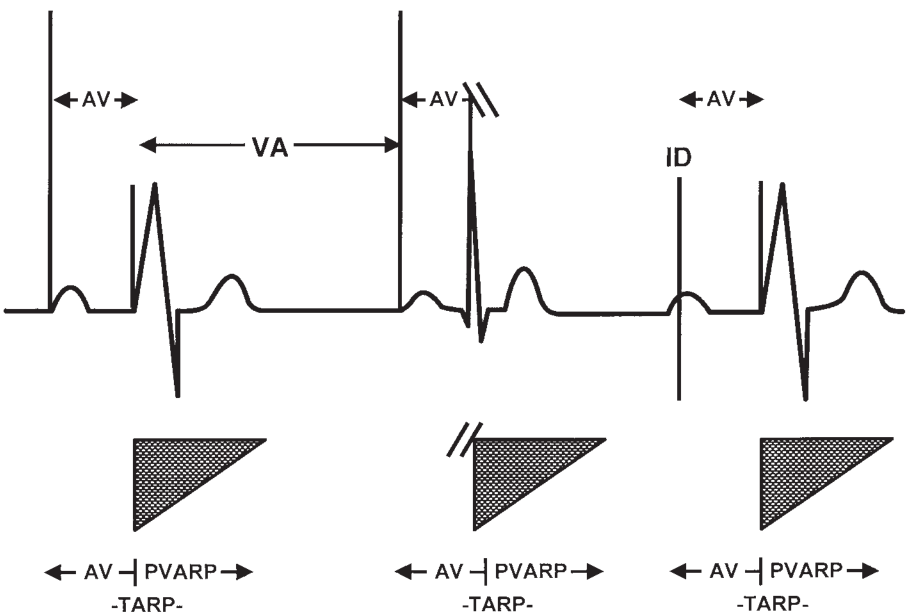
PORTIONS OF PACEMAKER TIMING CYCLES

Refractory Periods

Every pacemaker capable of sensing must include a refractory period in its basic timing cycle. Refractory periods prevent the sensing of known but clinically


AV
LR
Complete inhibition
P-synchronous
Atrial pacing
AV sequential

A


AV
VA
AV
AV
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AV PVARP
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AV PVARP
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AV PVARP
-TARP-

B

inappropriate signals, such as the evoked potential and repolarization (T wave).

In a single-chamber system that is otherwise capable of sensing (either the inhibited or the triggered mode), each sensed or paced event is followed by a refractory period. Once this timing period ends, the sense amplifier becomes alert and is receptive to the detection of native signals. If an appropriate event, such as a PVC, coincides with the VRP, it is not detected, and competition between the pacemaker and the intrinsic activity may occur. The refractory period of a pacemaker is analogous to the refractory period of the heart (QT interval). During the cardiac refractory period, a stimulus delivered to the heart is ineffective because the myocardium is already depolarized and a subsequent depolarization cannot occur until the resting membrane potential is reestablished. Like the heart, the pacemaker has a refractory period consisting of two components. The first is the absolute refractory period, during which native activity cannot be detected. More recently, this has been called a *blanking period*. The terminal portion of the refractory period is relative when events can be detected, but they are not used to trigger or reset an output pulse. Rather, they are used to detect rapid signals. If these signals exceed 400 to 600 cycles per minute (which is above the physiologic range), they are labeled *electrical noise*. Rather than be inhibited by these inappropriate signals, the pacemaker is designed to adopt asynchronous behavior, which is termed *noise mode response*. In the recent generation of dual-chamber pacing systems, rapid events detected on the atrial channel, but not the ventricular channel, help the device detect pathologic atrial rates and initiate automatic mode switching (see "Mode Switching," below).

In a DDD system, a sensed or paced atrial event initiates an atrial refractory period (ARP) and also initiates the AVI (Fig. 6.14B). During this portion of the timing cycle, the atrial channel is refractory to another native atrial event; nor does atrial pacing occur during this period. Atrial pacing occurs only at the end of the AVI or later (see "Upper Rate Behavior," discussed subsequently). A

Figure 6.14. A: The timing cycle in DDD consists of an LRL, an AVI, a VRP, a PVARP, and a URL. There are four variations of the DDD timing cycle. If intrinsic atrial and ventricular activity occur before the LRL times out, both channels are inhibited and no pacing occurs **(first panel)**. If a P wave is sensed before the VAI is completed (the LRL minus the AVI), output from the atrial channel is inhibited. The AVI is initiated, and if no ventricular activity is sensed before the AVI terminates, a ventricular pacing artifact is delivered, that is, P-synchronous pacing **(second panel)**. If no atrial activity is sensed before the VAI is completed, an atrial pacing artifact is delivered, which initiates the AVI. If intrinsic ventricular activity occurs before the termination of the AVI, ventricular output from the pacemaker is inhibited, that is, atrial pacing **(third panel)**. If no intrinsic ventricular activity occurs before the termination of the AVI, a ventricular pacing artifact is delivered, that is, AV sequential pacing **(fourth panel)**. **B:** Potential pacing combinations that can occur in the DDD pacing mode. The intrinsic P wave is sensed during the early portion of the P wave. The AVI is initiated at the point of the intrinsic deflection (ID) of atrial activity, as seen on the atrial electrogram. (Modified from Medtronic, Minneapolis, MN.)

sensed or paced ventricular event initiates a VRP. (A VRP is always part of the timing cycle of any pacing system with ventricular pacing and sensing.) The VRP prevents sensing of the evoked potential and the resultant T wave on the ventricular channel of the pacemaker. A sensed or paced ventricular event also initiates a refractory period on the atrial channel (PVARP).[13,14] The PVARP may prevent atrial sensing of a retrograde P wave (see "Endless-Loop Tachycardia," below), but the PVARP alone may not prevent sensing of far-field ventricular events in devices with an automatic mode-switching algorithm. The combination of the PVARP and the AVI forms the total atrial refractory period (TARP). The TARP, in turn, is the limiting factor for the maximum sensed atrial rate that the pacemaker can sense and, hence, track. For example, if the AVI is 150 milliseconds and the PVARP is 250 milliseconds, the TARP is 400 milliseconds, or 150 ppm. In this case, a paced ventricular event initiates the 250-millisecond PVARP, and only after this interval has ended can an atrial event be sensed. If an atrial event is sensed immediately after the termination of the PVARP, the sensed atrial event initiates the AVI of 150 milliseconds. On termination of the AVI, in the absence of an intrinsic R wave, a paced ventricular event occurs, resulting in a VV cycle length of 400 milliseconds, or 150 ppm. Programming a long PVARP limits the upper rate by limiting the maximum sensed atrial rate (Fig. 6.15).[15,16] If the native atrial rate were 151 bpm, every other P wave would coincide with the PVARP, not be sensed, and hence not

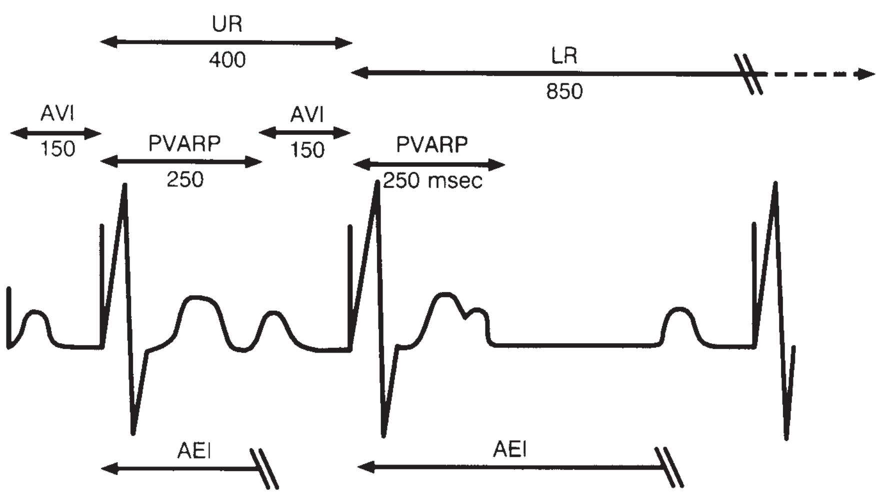


Figure 6.15. In the DDD pacing mode, the upper rate (UR) is limited by the AVI and the PVARP. In this example, the AVI is 150 milliseconds and the PVARP is 250 milliseconds, for a TARP of 400 milliseconds (this is equal to 150 ppm). As shown, after the first paced ventricular complex, a P wave occurs just after the completion of the PVARP. This P wave is sensed, initiates the AVI, and is followed by another paced ventricular complex. The subsequent P wave occurs within the PVARP and is therefore not sensed. The DDD response is to wait for the next intrinsic P wave to occur, as in this example, or for the AEI to be completed, whereupon AV sequential pacing occurs.

be tracked; so the effective paced rate would be approximately 75 ppm, or half the atrial rate.

In a pacemaker with a mode-switching algorithm "on," the pacemaker must be able to detect higher atrial rates, even if the native P waves coincide with the PVARP. Although these P waves may not be tracked, the pacemaker is capable of monitoring events that coincide with the refractory period to recognize rapid pathologic atrial rates. Thus, the system can switch from a tracking mode (DDD) to a nontracking mode (VVI or DDI), so that the first of the pathologic atrial events that occur during the atrial alert period is not tracked.

Atrioventricular Interval

The AVI, often poorly understood, should be considered a single interval with two subportions (Fig. 6.16A).[17] For most dual-chamber systems, the atrial

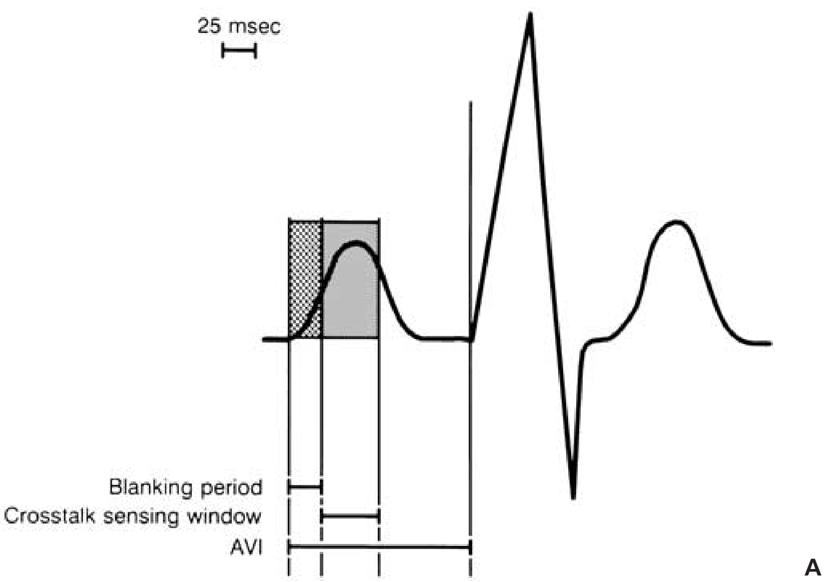


Figure 6.16. **A:** The AVI should be considered as a single interval with two subportions. The entire AVI corresponds to the programmed value, that is, the interval following a paced or sensed atrial beat allowed before a ventricular pacing artifact is delivered. The initial portion of the AVI is the blanking period. This interval is followed by the crosstalk sensing window. **B:** If the ventricular sensing circuit senses activity during the crosstalk sensing window, a ventricular pacing artifact is delivered early, usually at 100 to 110 milliseconds after the atrial event. This has been referred to as "ventricular safety pacing," "110-millisecond phenomenon," and "nonphysiologic AV delay." **C:** The initial portion of the AVI in most dual-chamber pacemakers is designated as the blanking period. During this portion of the AVI, sensing is suspended. The primary purpose of this interval is to prevent ventricular sensing of the leading edge of the atrial pacing artifact. Any event that occurs during the blanking period, even if it is an intrinsic ventricular event (as shown in this figure), is not sensed. In this example, the ventricular premature beat that is not sensed is followed by a ventricular pacing artifact delivered at the programmed AVI and occurring in the terminal portion of the T wave.

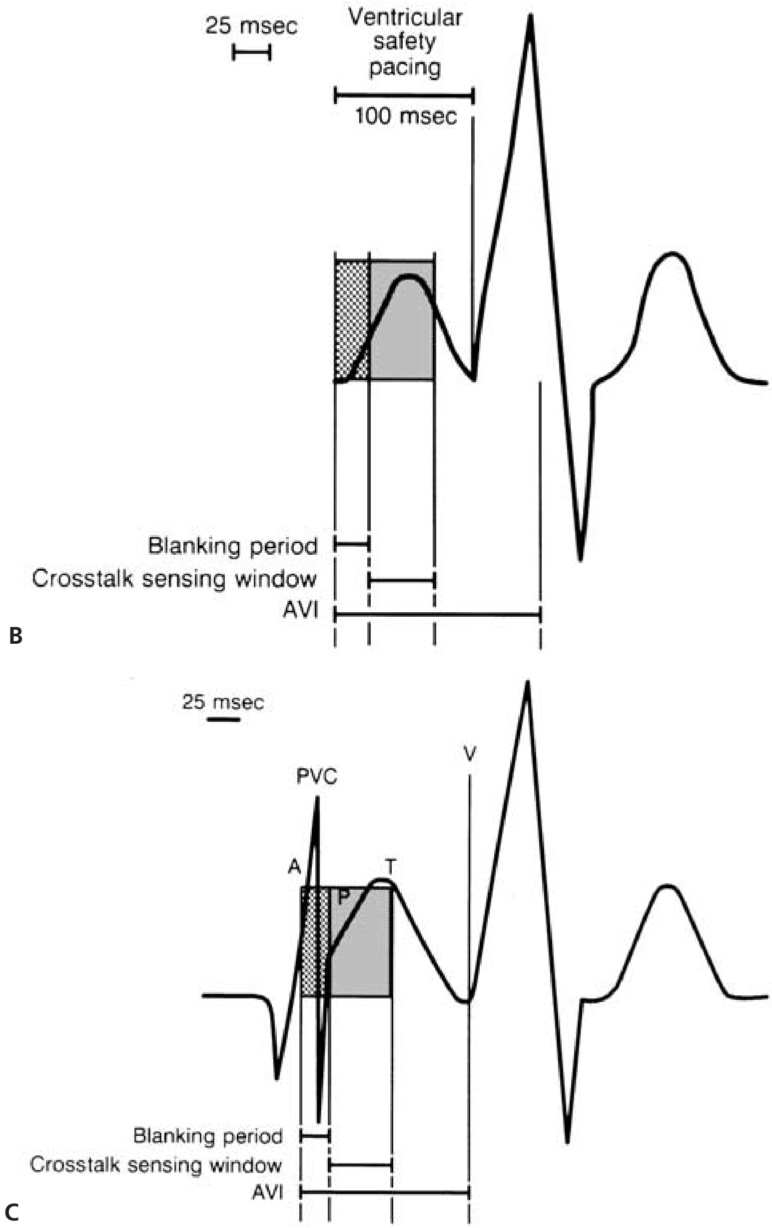


Figure 6.16. *Continued*

channel is totally refractory to the detection of other atrial signals that may occur during the AVI. In most devices, only the first portion of the AVI is absolutely refractory. The terminal portion is a relative refractory period, to assist in the detection of rapid pathologic atrial rhythms for purposes of mode switching (Fig. 6.17).

Atrial output also triggers a timing period on the ventricular channel, known as the *ventricular blanking period*. It coincides with the earliest portion of the AVI, and its purpose is to avoid sensing of an event or a stimulus of one channel in the opposite channel.[18–20]

If the atrial pacing artifact were sensed by the ventricular sensing circuit, ventricular output inhibition would result, i.e., crosstalk. To prevent crosstalk, the leading edge of the atrial pacing artifact is masked, or blanked, by rendering the ventricular sensing circuit absolutely refractory during the very early portion of the AVI (Fig. 6.16B). In DDD pacemakers, the blanking period may be programmable, ranging from 12 to 125 milliseconds. The blanking period is traditionally of short duration because it is important for the ventricular sensing circuit to be returned to the "alert" state relatively early during the AVI so that intrinsic ventricular activity can inhibit pacemaker output if it occurs before the AVI ends. The potential exists for signals other than those of intrinsic ventricular activity to be sensed and inhibit ventricular output. The greatest concern is crosstalk.[19,21] Even though the leading edge of the atrial pacing artifact is effectively ignored because of the blanking period, the trailing edge of the atrial pacing artifact occurring after the blanking period can occasionally be sensed on the ventricular channel. In a pacemaker-dependent patient, inhibition of ventricular output by crosstalk results in asystole. To prevent such an outcome, a safety mechanism is present.

If activity is sensed on the ventricular sensing circuit in a given portion of the AVI immediately after the blanking period (this second portion of the AVI

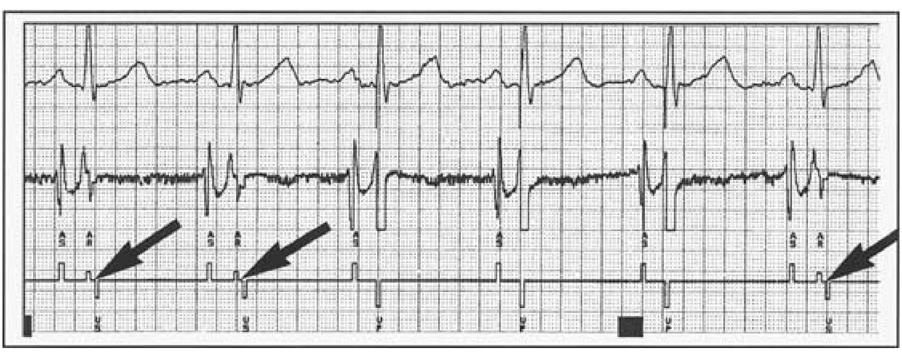


Figure 6.17. Surface ECG, atrial electrogram, and event markers *(arrows)* demonstrating occasional AR complexes, events that are occurring within the ARP. They coincide with the QRS complex but are detected on the atrial channel before being detected by the pacemaker on the ventricular channel.

has been called the "ventricular triggering period" or the "crosstalk sensing window"), it is assumed that crosstalk cannot be differentiated from intrinsic ventricular activity. To prevent catastrophic ventricular asystole, a ventricular pacing artifact is delivered early—at an AVI of 100 to 120 milliseconds, although in some pulse generators this interval is programmable for 50 to 150 milliseconds (Fig. 6.16C).[22] If the signal sensed is indeed crosstalk, a paced ventricular complex delivered at the abbreviated interval prevents ventricular asystole. In addition, AV pacing at a shorter-than-programmed AVI on the ECG indicates the occurrence of crosstalk and allows the pacemaker to be programmed to eliminate this behavior. Elimination of crosstalk may be accomplished by extending the ventricular blanking period, decreasing atrial output, or reducing the ventricular sensitivity. Or, if true intrinsic ventricular activity occurs during the early portion of the AVI, the safety mechanism results in delivery of a ventricular pacing artifact within or immediately after the intrinsic beat. This delivery is safe because the ventricle is refractory, no depolarization results from the pacing artifact, and the pacing artifact is delivered too early to coincide with ventricular repolarization or a vulnerable period. This event has been referred to as "ventricular safety pacing," "nonphysiologic AV delay," or the "110-millisecond phenomenon." Although the safety pacing phenomenon accompanying a late-cycle PVC has been interpreted as a sensing failure, it actually reflects normal sensing. Pacemaker behavior changes with respect to a ventricular event that is sensed during the "crosstalk sensing" window. The response is altered in comparison with an event sensed at any other time during the ventricular alert period. Sensing during this special brief timing period results in a triggered rather than an inhibited output. Unlike single-chamber function in which the triggered mode rapidly delivers an output pulse as soon as an event is detected, the R wave that occurs in the earliest portion of this special detection interval triggers an output at the end of the safety pacing interval.

After the blanking period and the crosstalk sensing window have timed out, the ventricular sensing circuit returns to the alert status, in which a detected event causes the output pulse to be reset.

Differential Atrioventricular Interval: If AVIs initiated by a sensed event and those initiated by a paced event show consistent differences, the most likely explanation is a differential AVI. As noted in the introduction to this section, a differential AVI is an attempt to provide an interatrial conduction time of equal duration whether atrial contraction is paced or sensed. The PV interval initiated with atrial sensing commences only when the atrial depolarization is detected by the pacemaker and commonly occurs 20 to 60 milliseconds after the onset of the P wave seen on a surface ECG. Conversely, the AVI initiated with atrial pacing commences immediately with the pacing artifact, not with atrial depolarization. The AVI that follows a sensed atrial event should therefore be shorter than one that follows a paced atrial event (Fig. 6.18) in an effort to achieve similar functional AVIs, whether the atrial event is paced or sensed. The AVI differential is programmable in some pacemakers and preset in others.

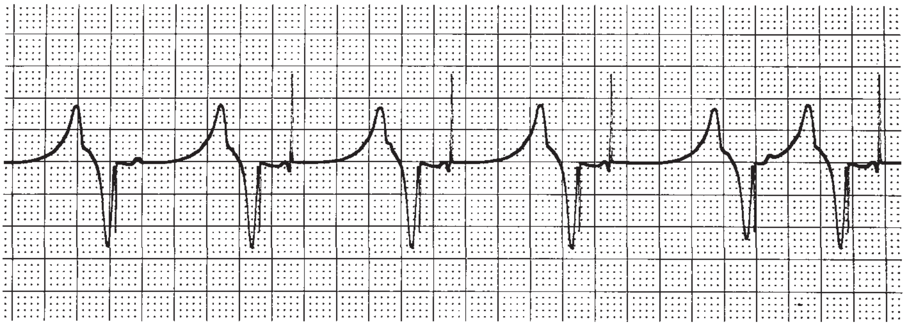
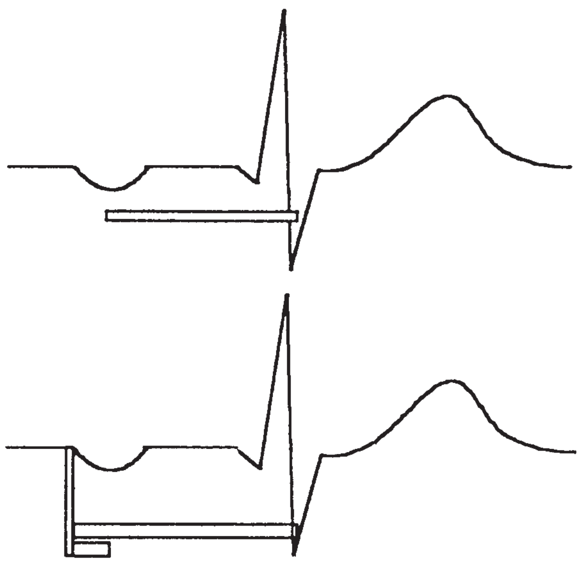


Figure 6.18. ECG tracing demonstrating differential AVI. The AVI is 50 milliseconds longer than the PV interval. (From Relay Models 293-03 and 294-03. Intermedics Cardiac Pulse Generator Physician's Manual. Angleton, Texas: Intermedics, 1992. By permission of Intermedics.)



AV Delay Hysteresis = A-R Interval - P-R Interval

Figure 6.19. Schematic diagram of one manufacturer's differential AVI, designated "AV delay hysteresis." (Modified from Chorus II Model 6234, 6244 Dual Chamber Pulse Generator Physician's Manual. Minnetonka, Minnesota: ELA Medical, 1994.)

One DDD pacemaker automatically calculates the AVI differential between paced and sensed atrial events.[23] When an atrial paced event occurs, the AR interval is measured. When an atrial sensed event follows an atrial paced event, a new PR interval is measured. The AV delay hysteresis is set equal to the maximum value (AR or PR) minus the PR interval (Fig. 6.19).

Most dual-chamber pacemakers allow the paced and sensed AV delays to be programmed independently. Although the two may be nominally different, wider differences up to 100 milliseconds are programmable.

Rate-Variable or Rate-Adaptive Atrioventricular Interval: Most DDD and DDDR pacemakers can shorten the AVI as the atrial rate increases, either by an increase in sinus rate or by a sensor-driven increase in paced rate (Fig. 6.20). Rate-adaptive or rate-variable AVI is intended to optimize cardiac output by mimicking the normal physiologic decrease in the PR interval that occurs in the normal heart as the atrial rate increases.[24–26] The rate-related shortening of the AVI may also improve atrial sensing by shortening the TARP and thereby extending the time for the ASW.

Rate-adaptive AVI may be designed in several ways. The more common method is to allow linear shortening of the AVI from a programmed baseline AVI to a programmed minimum AVI. Another method allows a limited number of stepwise shortenings of the AVI. These steps may or may not be programmable.

Atrioventricular Interval Hysteresis: The term *AVI hysteresis* has been used variously but most commonly describes alterations in the paced AVI relative to the patient's intrinsic AV conduction. For example, a longer paced AVI is permitted, to allow maintenance of intrinsic AV conduction. However, once the intrinsic PR or AR interval triggers the programmed AVI hysteresis, consistent AV pacing at the programmed AVI occurs. Commonly, AVI hysteresis is programmed by selecting the desired AV delay during pacing with an additional programmable delta. If there is AV pacing, the system periodically extends the AV delay by the programmed delta. If a native R wave is detected within this extended interval, the longer interval remains in place and results in functional single-chamber atrial pacing. However, with the first cycle of AV pacing, which may occur with a transient increase in vagal tone or even intermittent pathologic AV block, the AV delay returns to the programmed value.

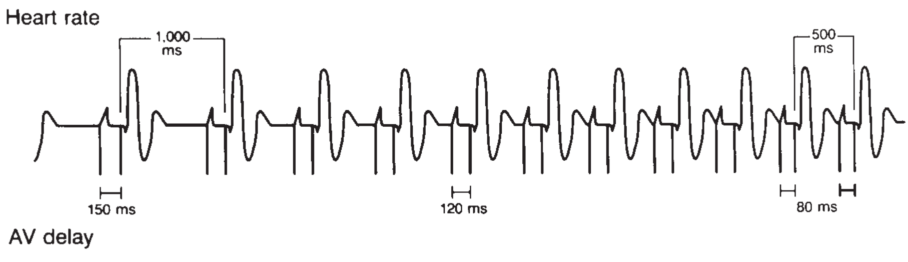


Figure 6.20. As heart rate increases, AV delay dynamically adapts to the change in cycle length. (From Hayes DL, Ketelson A, Levine PA, et al. Understanding timing systems of current DDDR pacemakers. Eur JCPE 1993;3:70–86. By permission of Mayo Foundation.)

This programming accomplishes two goals. In a patient with a normal ventricle, normal ventricular activation sequence (narrow QRS), and a normal PR interval, single-chamber atrial pacing provides hemodynamics superior to those of dual-chamber pacing. Ventricular stimulation causes a disordered ventricular activation sequence. However, an AV delay that is too long, as in first-degree AV block, may be hemodynamically deleterious. In this situation, hemodynamics may be superior with a shorter AV delay despite the disordered ventricular activation sequence. AVI hysteresis allows for both a longer AV delay when AV nodal conduction is intact and a shorter AVI when conduction is compromised.

Hysteresis Programming

Programming of hysteresis permits prolongation of the first pacemaker escape interval after a sensed event. A pacemaker programmed at a cycle length of 1000 milliseconds (60 bpm) and a hysteresis of 1200 milliseconds (50 bpm) allows 200 milliseconds more for another sensed QRS complex. If another QRS complex is not recognized, then the pacemaker continuously stimulates the heart at the programmed rate of 60 bpm, an escape interval of 1000 milliseconds (Fig. 6.21), until a sensed event restarts the cycle. The advantage of hysteresis in a single-chamber pacing mode is the ability to maintain spontaneous AV synchrony as long as possible.[2] This feature may prevent symptomatic retrograde VA conduction. In patients with VVI pacing and pacemaker syndrome, hysteresis provides reliable higher rate backup pacing while increasing the potential for maintaining the patient's intrinsic rhythm.

Several types of hysteresis may be programmable options in some dual-chamber pacemakers. In the first-generation algorithm, a native event had to be sensed to reestablish the hysteresis escape interval. The native complex had to occur at a rate faster than the basic pacing rate. If the basic pacing rate was relatively high, the system may have continued pacing long after the need for pacing had resolved. Therefore, *search hysteresis* was introduced. In search hysteresis, once a specific number of timing cycles at the more rapid rate (the number of cycles may be fixed or programmable) has occurred, the prolonged escape interval is permitted to allow manifestation of a slower intrinsic rate—that is, a rate higher than the programmed LRL. If intrinsic rhythm does not return at a rate exceeding the programmed lower rate, stimulation resumes at the more rapid rate for a given number of cycles (Fig. 6.22). This feature has been further modified in some systems to prevent an isolated PVC from resetting the basic dual-chamber pacing interval. Rather, resetting the hysteresis escape interval requires a sensed P wave to produce either a PR or a PV complex that inhibits the higher rate of pacing and reestablishes the hysteresis feature.

Another feature can be considered a refinement of search hysteresis.[3] A "sudden bradycardia response" or "rate drop response" (RDR) reacts to a defined drop in heart rate. When this occurs, the pacemaker feature intervenes by pacing at an elevated rate in both chambers for a specific, programmed duration (Fig. 6.23). At the conclusion of the programmed duration of more rapid

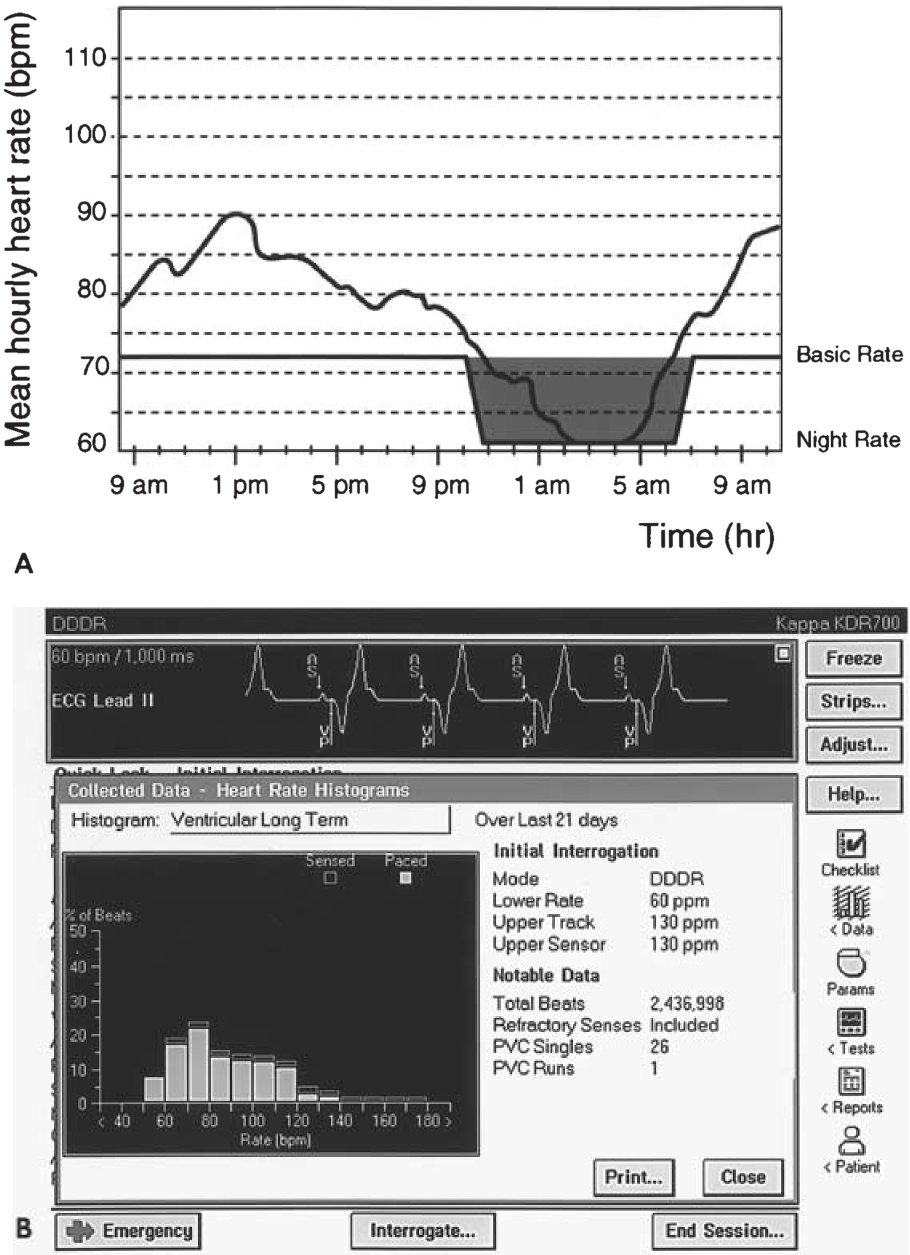


Figure 6.21. **A:** Printout of telemetric data of patient's mean hourly heart rate. The pacemaker is programmed to a lower, or basic, rate of 72 bpm and to a sleep rate, or night rate, of approximately 60 bpm. The graph demonstrates the slower rates allowed during night hours, in this example from 10 PM to 7 AM. **B:** Heart rate histogram from a patient with a DDDR pacemaker programmed to a lower rate of 60 bpm and an upper rate of 130 bpm. However, the histogram is compatible, with approximately 7% of the rates being less than 60 bpm. This can be explained by a sleep rate programmed to 50 bpm. (From Lloyd MA, Hayes DL, Friedman PA. Programming. In: Hayes DL, Lloyd MA, Friedman PA, eds. Cardiac Pacing and Defibrillation: A Clinical Approach. Armonk, NY: Futura, 2000:247–323. By permission of Mayo Foundation.)

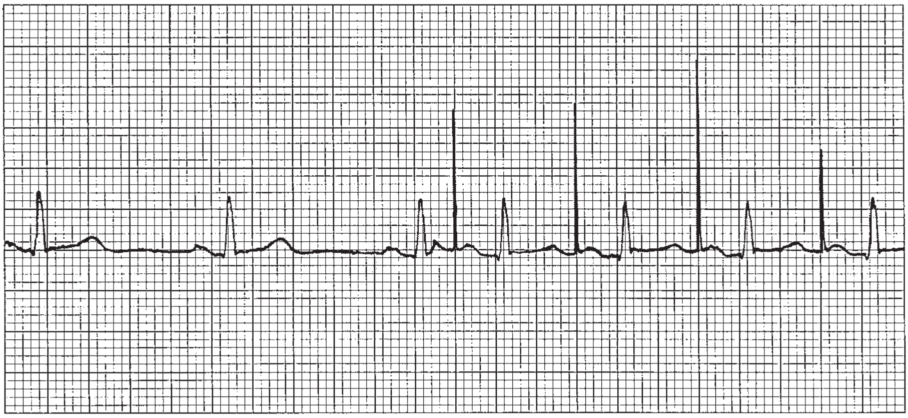


Figure 6.22. Onset of pacing in a DDDR pacemaker programmed to a lower rate of 100 bpm, hysteresis at 65 bpm, when the intrinsic rate has declined to 63 bpm. After 256 cycles of pacing at 100 bpm, pacing is suspended for the pacemaker to "search" for the intrinsic lower rate. If the lower rate is greater than the hysteresis rate, pacing is inhibited until the rate again falls below the hysteresis rate. (From Lloyd MA, Hayes DL, Friedman PA. Programming. In: Hayes DL, Lloyd MA, Friedman PA, eds. Cardiac Pacing and Defibrillation: A Clinical Approach. Armonk, NY: Futura, 2000:247–323. By permission of Mayo Foundation.)

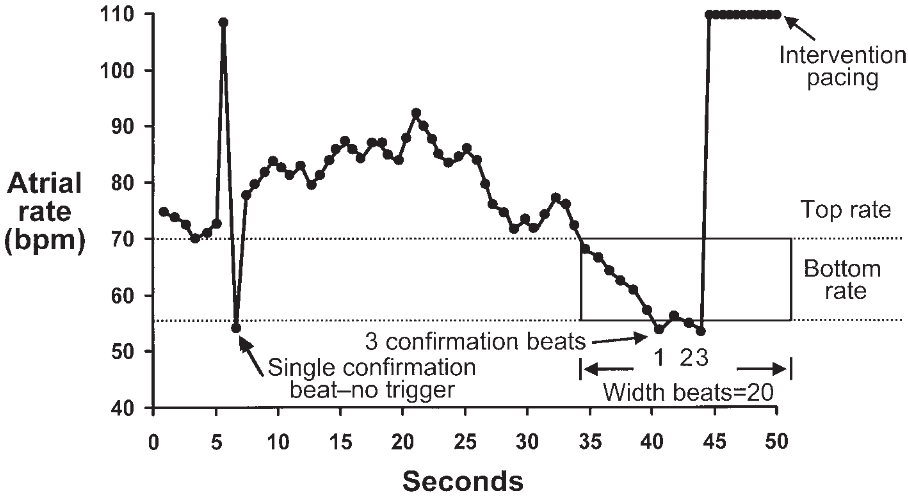


Figure 6.23. Diagrammatic representation of RDR. This algorithm requires that "top" and "bottom" rates be defined for rate drop detection, a specific number of beats, width over which the rate may drop, and the pacing rate that results if criteria are met, that is, the intervention rate. Three confirmation beats below the bottom rate must occur before therapy is triggered. In the early portion of this diagram, a single beat falls below the bottom rate but fails to trigger intervention because confirmation is not met. (From Lloyd MA, Hayes DL, Friedman PA. Programming. In: Hayes DL, Lloyd MA, Friedman PA, eds. Cardiac Pacing and Defibrillation: A Clinical Approach. Armonk, NY: Futura, 2000:247–323. By permission of Mayo Foundation.)

pacing, the pacing rate gradually returns to the programmed lower rate. Several programmable detection algorithms are available. The first algorithm available was "drop detect," in which the pacemaker monitors a drop in heart rate that must satisfy two programmable requirements to trigger an intervention, namely, the programmable "drop size," which is the number of beats the rate must fall, and the "detection window," which is the amount of time monitored for a rate drop (this is a programmable interval) (Fig. 6.24). The "nominal" values for RDR are not successful for everyone.

In the "low rate detect" algorithm, therapy is triggered when pacing occurs at the programmed lower rate for the programmable consecutive number of "detection beats." This detection method can be used as a backup to the "drop detect" method if the sudden drop in rate varies between slow and fast (Fig. 6.25).[4]

Dual-chamber rate hysteresis has multiple variations and different levels of complexity. Although the primary mode of therapy for vasovagal syncope is pharmacologic, it is not always 100% successful. Another treatment objective is dual-chamber pacing support at a relatively high rate during each spell, which may be effective in ameliorating if not totally eliminating the episodes. Because patients with neurocardiogenic syncope have a normal rhythm at other times, the hysteresis circuit allows for pacing at the higher rate only during the spell (when the native heart rate falls precipitously) and otherwise remains inhibited.[27,28]

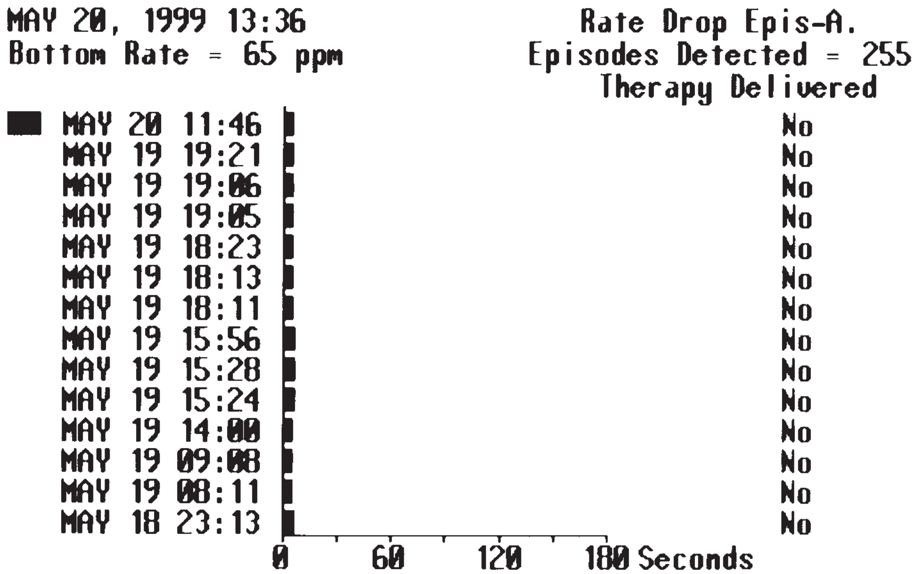
BASE RATE BEHAVIOR

The way a pacemaker behaves in response to a sensed ventricular signal varies among manufacturers and even among devices from the same manufacturer. Dual-chamber pacemakers have historically been designed with a ventricular-based timing system, an atrial-based timing system, or a hybrid of these two systems.[3,29] Designation of a pacemaker's timing system as atrial-based or ventricular-based gained increased importance with the advent of rate-adaptive pacing. The difference between atrial-based and ventricular-based dual-chamber pacemakers was of little clinical importance in non–rate-adaptive pacemakers, although the difference created some minor confusion in interpretation of paced ECGs.

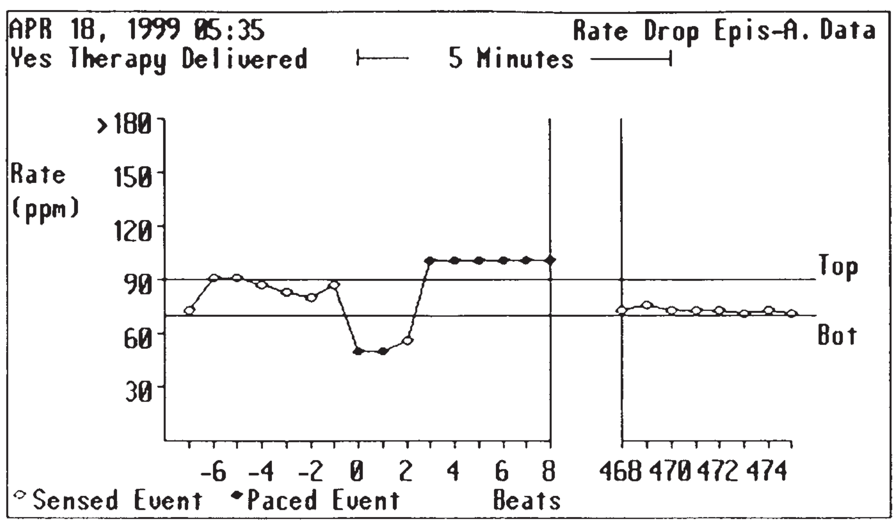
With the refinement of timing systems, use of a specific system has once again become less important. A description of pure atrial-based and ventricular-based timing systems appears below. However, few contemporary dual-chamber pacemakers are "pure" atrial-based or ventricular-based systems. The majority is in some way hybrid, designed specifically to avoid the potential rate variations or limitations that could occur with either pure timing system.

Ventricular-Based Timing

In a ventricular-based timing system, the AEI is "fixed." A ventricular sensed event occurring during the AEI resets this timer, causing it to start again (Fig.



A



B

Figure 6.24. **A:** The RDR counters indicate that the pacemaker had documented multiple episodes of sudden rate drop. However, "therapy"—that is, a response to the sudden drop in rate with an increase in pacing rate for a programmed period—had not been initiated. **B:** With a pacemaker in place and RDR that had been programmed "on" but not initiated because of the programmed parameters, adjusting the RDR parameters would be reasonable. For this patient, the RDR criteria were programmed more sensitively. When the patient returned, the rate counter was again full, with 255 episodes detected and therapy delivered on two occasions. The second printout details the event on April 18 at 05:35 when therapy was delivered. The diagram documents a sudden decrease in rate; RDR was met and therapy delivered. (From Lloyd MA, Hayes DL, Friedman PA. Programming. In: Hayes DL, Lloyd MA, Friedman PA, eds. Cardiac Pacing and Defibrillation: A Clinical Approach. Armonk, NY: Futura, 2000:247–323. By permission of Mayo Foundation.)

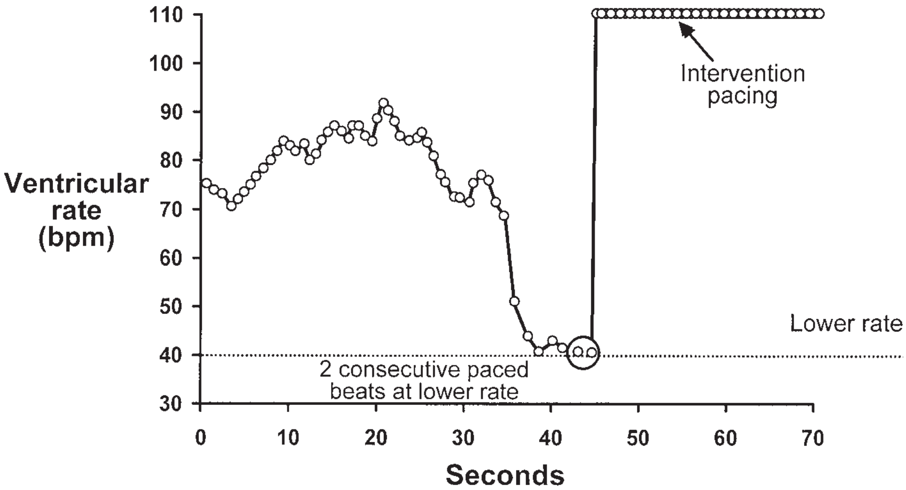


Figure 6.25. In the low rate detect algorithm (Medtronic, Inc.), when pacing occurs at the programmed lower rate for the programmable consecutive number of detection beats, therapy is triggered. Low rate detect may be used as a backup to the drop detect method if the sudden drop in rate varies between slow and fast. (From Lloyd MA, Hayes DL, Friedman PA. Programming. In: Hayes DL, Lloyd MA, Friedman PA, eds. Cardiac Pacing and Defibrillation: A Clinical Approach. Armonk, NY: Futura, 2000:247–323. By permission of Mayo Foundation.)

6.26, top). A ventricular sensed event occurring during the AVI both terminates the AVI and initiates an AEI (see Fig. 6.12, top). If there is intact conduction through the AV node after an atrial pacing stimulus such that the AR interval (atrial stimulus to sensed R wave) is shorter than the programmed AVI, the resulting paced rate accelerates by a small amount. This response is demonstrated in Figure 6.12 (top).

This phenomenon is best understood by example. In a pacemaker programmed to an LRL of 60 bpm (a pacing interval of 1000 milliseconds) that has a programmed AVI of 200 milliseconds, the AEI is 800 milliseconds (AEI = LRL − AVI). If AV nodal function permits conduction in 150 milliseconds (AR interval + 150 milliseconds), the conducted or sensed R wave inhibits ventricular output. This, in turn, resets the AEI, which remains stable at 800 milliseconds. The resulting interval between consecutive atrial pacing stimuli is 950 milliseconds (AEI + AR interval), which is equivalent to a rate of 63 bpm, a rate slightly faster than the programmed LRL. When a native R wave occurs—for example, a ventricular premature beat during the AEI—the AEI is also reset. The pacemaker then recycles, resulting in a rate defined by the sum of the AEI and AVI. This escape interval is therefore equal to the LRL (Fig. 6.26, top). In both cases, the sensed ventricular event, an R wave, regardless of where it occurs, resets the AEI.

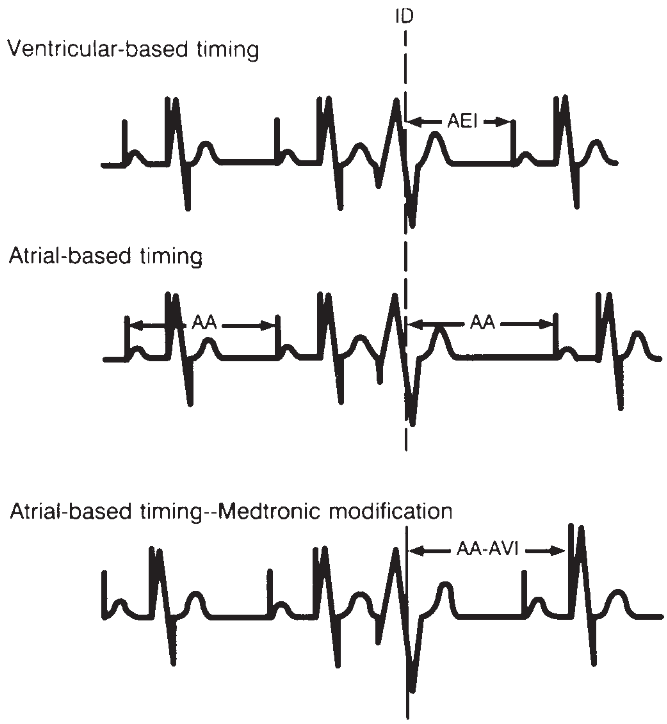


Figure 6.26. **Top:** Ventricular-based timing resets the AEI so that the recycled pacing interval is equal to the programmed base rate. **Middle:** Atrial-based timing resets the AA interval and then adds the AVI. Thus, the interval from the sensed R wave to the next paced ventricular beat exceeds the base rate interval, a form of obligatory hysteresis. **Bottom:** Medtronic modification of the AA timing subtracts the AVI from the AA interval. The resulting rhythm is identical to that seen with ventricular-based timing. (From Levine PA, Hayes DL, Wilkoff BL, Ohman AE. Electrocardiography of Rate-Modulated Pacemaker Rhythms. Sylmar, CA: Siemens-Pacesetter, 1990. By permission of Siemens-Pacesetter.)

Atrial-Based Timing

In an atrial-based timing system, the AA interval is fixed, whereas in a ventricular-based system, the AEI is fixed. As long as LRL pacing remains stable, there is no discernible difference between the two timing systems.

In a system with pure atrial-based timing, a sensed R wave occurring during the AVI inhibits ventricular output but does not alter the basic AA timing. Hence, the rate stays at the programmed LRL (see Fig. 6.12, bottom) during effective single-chamber atrial pacing. When a ventricular premature beat is sensed during the AEI, the timers are also reset, but the AA interval rather than the AEI is reset. The pacemaker counts out an AA interval and then adds the programmed AVI, in an attempt to mimic the compensatory pause commonly seen in normal sinus rhythm with ventricular ectopy—a form of obligatory hysteresis (Fig. 6.26, middle).

Other manufacturers have chosen to modify an atrial timing system. One DDDR pulse generator primarily uses modified atrial, or AA, timing, whereby an atrial sensed or paced event commonly resets the timing cycle of the device (much like the sinus node itself).[30] However, in certain situations (for example, after a PVC), an exception is made, and ventricular (VA) timing is used. Another manufacturer uses an atrial timing system that ignores the sensed R wave during stable AR pacing, which eliminates the rate acceleration that would be seen with ventricular-based timing designs.[31] This feature is modified when a native R wave or sensed premature ventricular event occurs after the VRP is completed. The AA interval is reset but only after the AVI is first subtracted (Fig. 6.27).

Comparison of Atrial-Based and Ventricular-Based Systems

When the heart rate is considered, usually the ventricular rate is paramount, because it, not the atrial rate, causes the effective (hemodynamic) pulse. During periods of 2:1 AV block at the lower rate, a ventricular-based timing system

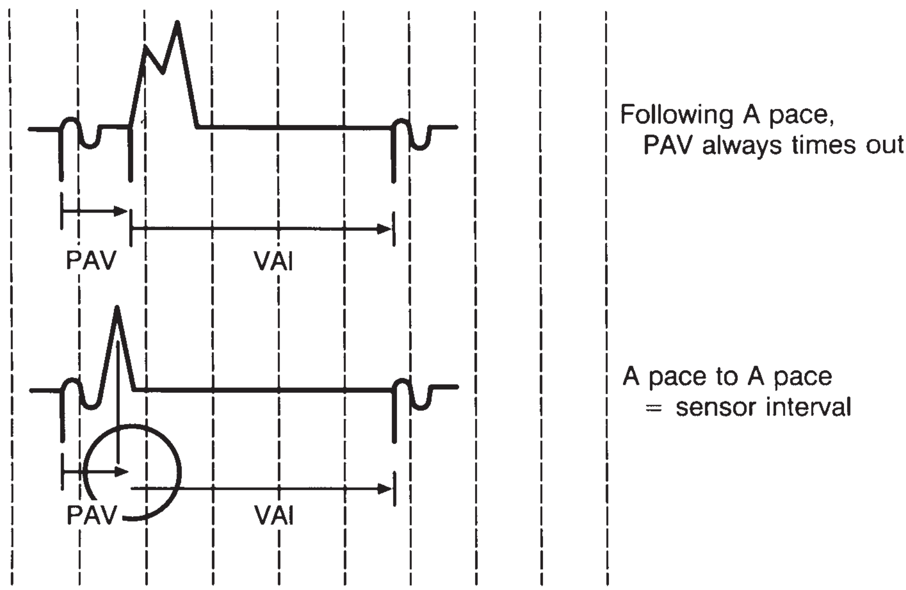


Figure 6.27. Ventricular-based versus atrial-based timing. The lower portion demonstrates atrial escape timing after an atrial (A) pace in atrial-based timing. With this timing, the AVI after atrial pacing (PAV) always times out, regardless of ventricular inhibition. The escape interval from one atrial pace to the next is equal to the sensor interval. VAI, interval from ventricular sensed or paced event to atrial paced event. (From Hayes DL, Ketelson A, Levine PA, et al. Understanding timing systems of current DDDR pacemakers. Eur JCPE 1993;3:70–86. By permission of Mayo Foundation.)

alternates between the programmed rate (AV pacing state) and a slightly faster rate (AR pacing state), as shown in Figure 6.28 (top).

In an atrial-based system, the alternation of the longer AVI with the shorter AR interval results in ventricular rates that are both faster and slower than the programmed base rate. This response is shown in Figure 6.28 (bottom).

Although ventricular-based timing may result in an increase in the paced rate during AR pacing (see "Effects of Ventricular- and Atrial-Based Timing Systems on DDDR Timing Cycles," below), the LRL is never violated. This is not the case with atrial-based timing. When an AV complex follows an AR complex, the effective paced ventricular rate for that cycle falls below the programmed LRL. A 2:1 AV block in an atrial-based timing system induces alternating cycles that are either faster or slower than, but never the same as, the programmed base rate (see Fig. 6.28, bottom).

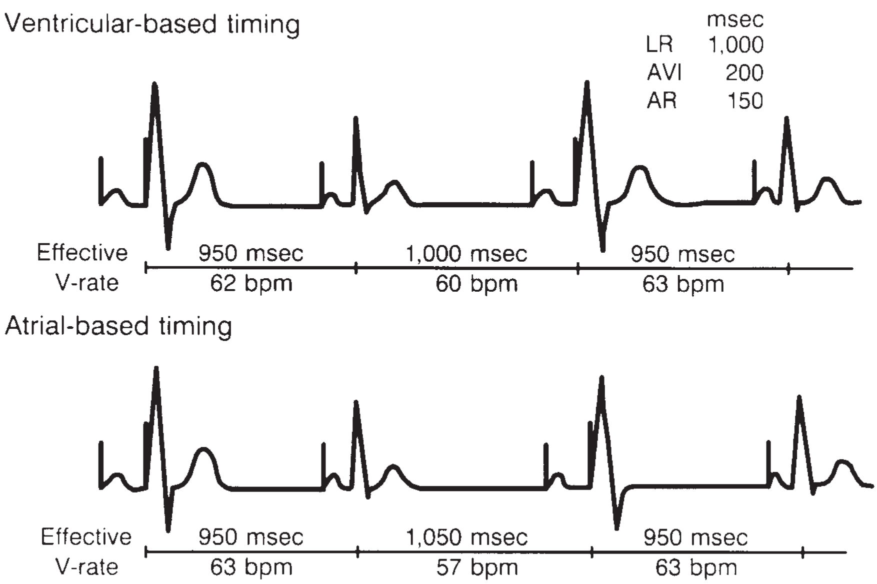


Figure 6.28. Diagrammatic representations of 2:1 AV block during base rate pacing. **Top:** With a ventricular-based timing system, the interval between consecutive AV and AR paced complexes is slightly shorter; hence, the rate is slightly faster than the programmed base rate. The interval between consecutive AR and AV paced complexes results in ventricular pacing at the base rate for that pacing cycle. **Bottom:** In an atrial-based timing system, the effective ventricular paced rate alternates between rates that are faster and slower than the programmed rate. The cycle between an AR and AV complex results in a ventricular rate that is slower than the programmed rate, a form of hysteresis. Meanwhile, the cycle between an AV and an AR complex causes the ventricular rate to be faster than the programmed rate. Atrial pacing is stable at the programmed rate, but it is the ventricular contraction that induces cardiac output. (From Levine PA, Hayes DL, Wilkoff BL, Ohman AE. Electrocardiography of Rate-Modulated Pacemaker Rhythms. Sylmar, CA: Siemens-Pacesetter, 1990. By permission of Siemens-Pacesetter.)

Interpretation of an ECG of a patient with a dual-chamber pacemaker is helped by knowing whether the pacemaker has atrial-based or ventricular-based timing. With a ventricular-based timing system, a pair of calipers set to the VAI can be used to measure backward from an atrial paced stimulus to the point of ventricular sensing, since a ventricular event, paced or sensed, always initiates the VAI.

A similar technique can be used in an atrial-based timing system, but only when a sensed ventricular complex occurs after the VRP ends. The calipers must be set to the AA interval before measuring backward from the atrial paced event that follows a ventricular sensed event. If one were to misidentify an atrial-based timing system as a ventricular-based system, an otherwise normal rhythm might be misinterpreted as T-wave oversensing or some other form of oversensing (see Fig. 6.26, middle).

Sensor Input to Base Rate Pacing

The sensor input to the pacing system temporarily adjusts the rate of the pacemaker. If the individual is active and rate modulation is enabled, the heart rate is determined by the faster of either the native rate or the sensor-determined rate. The sensor rate behaves in a manner identical to the programmed base rate. If the native rate is faster than the base rate, the pacemaker is either inhibited or tracks the atrial complexes. If the base rate is faster than the intrinsic rate, the heart rate is controlled by the pacemaker. Regardless of whether the programmed base rate or the sensor rate is in effect, pacing is always atrial in a dual-chamber pacing system. When the sensor input to the pacing system fluctuates, the rate changes.

Automatic Mode Switch Base Rate

On the basis of the older literature on lone atrial fibrillation,[32–35] higher heart rates are often needed to compensate for the loss of atrial transport. Thus, during paroxysmal atrial fibrillation in a patient with high-grade AV block and a pacemaker with mode-switching capability, the resting heart rate during the nontracking mode may be too low. This low intrinsic rate is of particular concern during protracted periods of pacing in the nontracking mode. For this reason, the ability to independently program a resting pacemaker rate in effect while the mode switch algorithm is engaged has been introduced to some devices. The programmed base rate might be 60 ppm during sinus rhythm and normal DDD function, whereas the base rate might be 80 to 90 bpm during atrial fibrillation with the system functioning in the DDI mode. If rate modulation were also activated, any increase in sensor-driven rates would start at the appropriate base for the functional pacing mode at the time.

Upper Rate Behavior

In the DDD mode of operation, acceleration of the sinus rate results in the sensed P wave terminating the AEI and initiating an AVI, an effect known as *P-wave synchronous ventricular pacing*. (If the PR interval is shorter than the PV interval—the time from an intrinsic P wave to a paced ventricular depolarization—the pacemaker is completely inhibited.) P-wave synchronous pacing occurs in a 1:1 relationship between the programmed LRL and the programmed URL. In other words, when the interval between consecutive native atrial events is longer than the TARP, each P wave occurs in the atrial alert period and is therefore sensed. Consequently, atrial output is inhibited while simultaneously triggering ventricular output after the AVI. However, when the interval between consecutive native atrial events is shorter than the TARP, some P waves are not sensed because, by definition, they fall into the TARP. The pacemaker goes into an abrupt fixed-block (2:1, 3:1, etc.) response, sensing only every other or every *n*th P wave, depending on the native atrial rate (Fig. 6.29). Programming a long PVARP results in the fixed-block response occurring at a relatively low tracking rate. The abrupt change in pacing rate when the fixed block occurs can result in serious symptoms, which frequently happened in early generation DDD pacemakers.

An additional timing circuit, known as the MTR interval,[9,15] better modulates the upper rate behavior. (The MTR interval has also been referred to as "upper rate limit" and "ventricular tracking limit.") This timing period defines the maximum paced ventricular rate or the shortest interval initiated by a sensed P wave at which a paced ventricular beat can follow a preceding paced or sensed ventricular event. The pacemaker has an upper rate behavior that mimics AV nodal Wenckebach behavior. The appearance is that of group beating, progressive lengthening of the PV interval, and intermittent pauses on the ECG when the native atrial rate exceeds the programmed MTR interval (Fig. 6.30). In these pacing systems, two timers must each complete their cycles for a ventricular stimulus to be released. These timing cycles are known as the AVI and the MTR interval. A sensed P wave initiates an AVI. If, on completion of the AVI, the

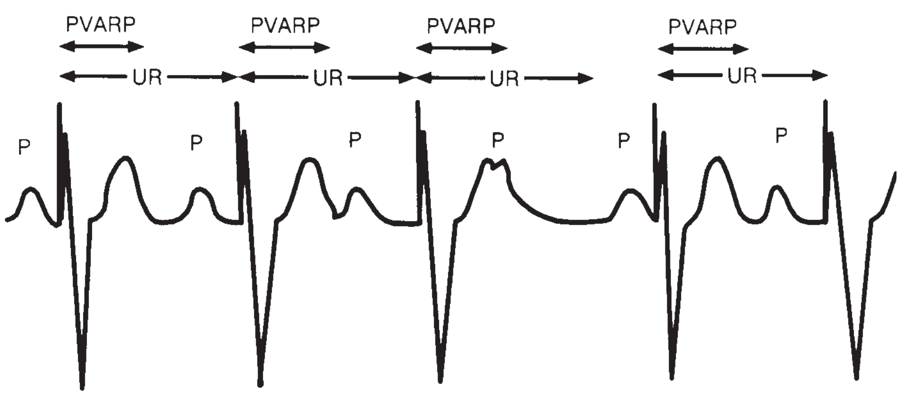


Figure 6.29. If the sinus rate becomes so rapid that every other P wave occurs within the PVARP, effective 2:1 AV block occurs; that is, every other P wave is followed by a ventricular pacing artifact.

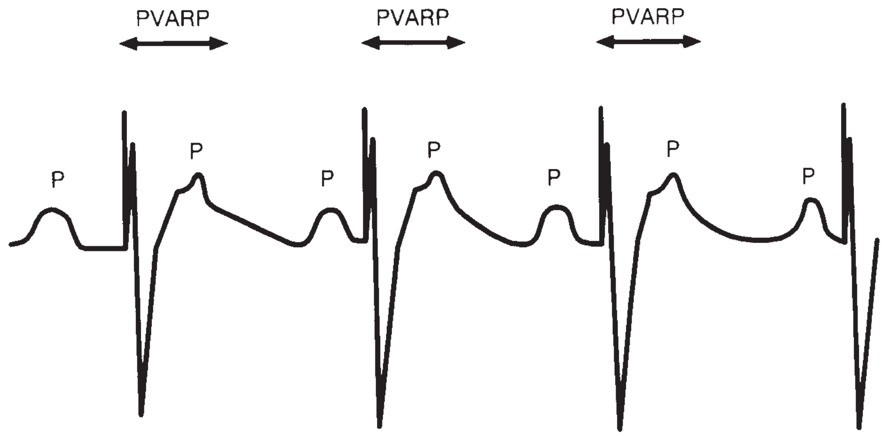


Figure 6.30. In the DDD pacing mode, the programmed upper rate limit (UR) cannot be violated regardless of the sinus rate. When a P wave is sensed after the PVARP, the AVI is initiated. If, however, delivering a ventricular pacing artifact at the end of the AVI would violate the UR, the ventricular pacing artifact cannot be delivered. The pacemaker would wait until completion of the UR and then deliver the ventricular pacing artifact. This action would result in a prolonged AVI.

MTR interval has been completed, a pacemaker stimulus is released at the programmed AVI. If the MTR interval has not yet been completed, the release of the ventricular output pulse is delayed until the MTR interval ends. This delay has the functional effect of lengthening the PV interval and places the ensuing ventricular paced beat closer to the next P wave. Both the PVARP and the MTR interval are initiated by a paced or sensed ventricular event. During Wenckebach upper rate behavior, a P wave eventually coincides with the PVARP, is not sensed, and is therefore ignored by the pacemaker, which results in a relative pause. The MTR interval is then able to complete its timing period, which depends on the atrial rate and programmed base rate, so that either the P wave that follows the unsensed P wave is tracked (restarting the cycle at the programmed AVI) or the pause is terminated by AV sequential pacing.

Thus, upper rate behavior can demonstrate Wenckebach-like behavior or go into abrupt fixed block (e.g., 2:1). It demonstrates 2:1 block behavior when the P wave falls into the TARP. If the MTR interval is longer than the TARP (TARP = AVI + PVARP), then Wenckebach-like behavior occurs. This can be summarized by the following equation: Wenckebach interval = MTR interval − TARP.

Therefore, if a positive number results, Wenckebach-like behavior occurs. In contrast, if a negative number results, fixed 2:1 AV block occurs. For example, if a patient's pacemaker is programmed to an AVI of 250 milliseconds, a PVARP of 225 milliseconds, and an MTR of 400 milliseconds, by the above equation the Wenckebach interval is 400 − (250 + 225), or a negative number. Therefore, when the atrial rate reaches 401 milliseconds, a 2:1 AV upper rate response is seen. If this patient's AVI is reprogrammed to 125 milliseconds, by the equation the Wenckebach interval is 400 − (125 − 225), or a positive number (+50 milliseconds). In the latter instance, when the atrial rate is 351 milliseconds, Wenckebach-like conduction is seen for a 50-millisecond interval. As the atrial rate increases further to 401 milliseconds, 2:1 AV block is noted.

Rate smoothing, a variation of upper rate behavior, was introduced by Cardiac Pacemakers, Inc. (Guidant, St. Paul, Minnesota) as a method of preventing marked changes in cycle length not only occurring at the URL of a DDD pacemaker but also any time the sinus rate is accelerating or decelerating.[36] (With rate smoothing, the pacemaker is programmed to a percentage change that is allowed between VV cycles, that is, 3%, 6%, 9%, or 12%. For example, if the VV cycle length is stable at 900 milliseconds during P-synchronous pacing, rate smoothing is "on" at 6%, and the sinus rate suddenly accelerates, the subsequent VV cycle cannot accelerate by more than 54 milliseconds, which is 6% of 900 milliseconds.) The ventricular rate is therefore relatively smooth, but sometimes at the expense of uncoupling AV synchrony (Fig. 6.31).

Because Wenckebach upper rate behavior results in the loss of a stable AV relationship and some patients may be symptomatic with both this and the resul-

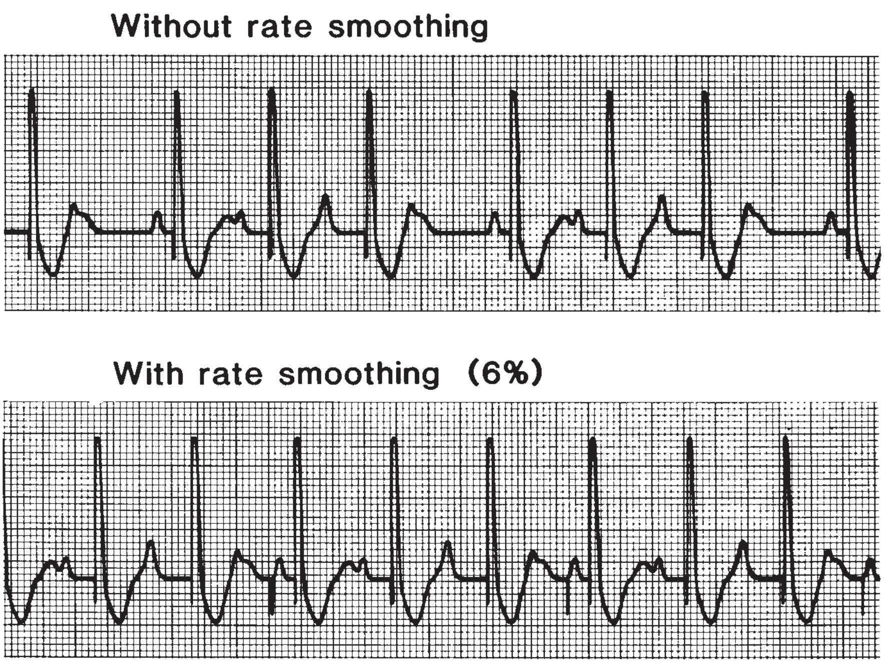


Figure 6.31. ECG demonstrating DDD pacing with true rate smoothing capabilities (6% of the preceding RR interval). With true rate smoothing, the Wenckebach interval is allowed to lengthen only 36 milliseconds over the preceding RR interval, at an MTR of 100 ppm. (Reprinted with permission from Cardiac Pacemakers, Inc., St. Paul, MN.)

tant pauses that occur when a P wave coincides with the PVARP and is not tracked, another upper rate behavior, fallback, is available in some devices. When the atrial rate exceeds the programmed MTR, the pacemaker continues to sense atrial activity but uncouples the native atrial rhythm from the ventricular paced complexes. The ventricular paced rate then slowly and progressively decreases to either an intermediate rate or the programmed base rate. This arrangement avoids the abrupt pauses that occur with both the Wenckebach and the fixed-block behaviors. When the atrial rate slows below either the MTR or the fall-back rate, depending on the design of the system, the desired AV relationship is restored.

Mode Switching

Mode switching refers to the ability of the pacemaker to automatically change from one mode to another in response to an inappropriately rapid atrial rhythm.[37] With mode switching, when the pacemaker is functioning in the DDDR mode, the algorithm automatically reprograms the pacemaker to the VVIR mode if specific criteria for a pathologic atrial rhythm are met. Mode switching is particularly useful for patients with paroxysmal supraventricular rhythm disturbances. In the DDD or DDDR pacing mode, if a supraventricular rhythm disturbance occurs and the pathologic atrial rhythm is sensed by the pacemaker, rapid ventricular pacing may occur (Fig. 6.32). Any pacing mode that eliminates tracking of the pathologic rhythm, for example, DDI, DDIR, DVI, or DVIR, also eliminates the ability to track normal sinus rhythm, which is usually the predominant rhythm. Mode switching avoids this limitation (Fig. 6.33).

Refinement of mode-switching algorithms has made this a successful feature (Fig. 6.34).[38] Mode switching functions by measuring intervals between

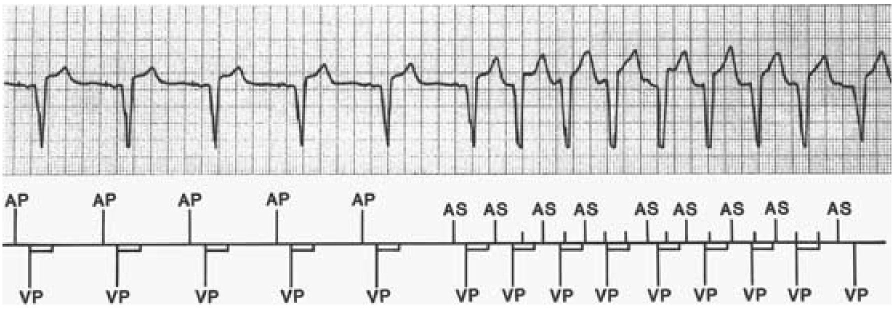


Figure 6.32. Resting ECG tracing demonstrating AV sequential pacing at lower rate (55 ppm) followed by paroxysmal atrial flutter with ventricular tracking at MTR (110 ppm). Diagram shows atrial paced events (AP), atrial sensed events (AS), and ventricular paced events (VP), with the PVARP noted by the rectangle. Short, unlabeled ticks represent atrial activity that occurs in the PVARP and is not sensed. (Diagram is based on Marker Channel, Medtronic, Inc., Minneapolis, MN.) (From Levine PA, Hayes DL, Wilkoff BL, Ohman AE. Electrocardiography of rate-modulated pacemaker rhythms. Sylmar, CA: Siemens-Pacesetter, 1990. By permission of Siemens-Pacesetter.)

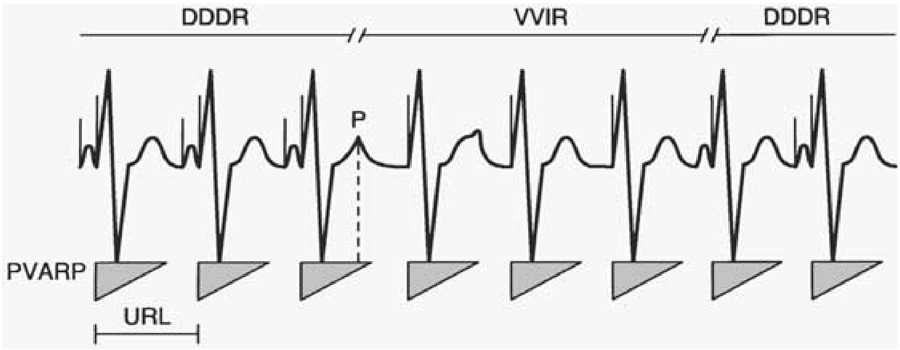


Figure 6.33. ECG appearance of mode switching. The first three cardiac cycles are due to sensor-driven AV sequential pacing, that is, DDDR pacing. After the third paced ventricular complex, a P wave occurs during the PVARP (*shaded triangles*) and initiates mode switching to the VVIR mode because the atrial rate has exceeded the URL. The pacing mode reverts to DDDR when the atrial rate falls below the programmed URL; that is, P waves fall outside the PVARP. (From Hayes DL. Timing cycles of permanent pacemakers. Cardiol Clin 1992;10:593–608. By permission of WB Saunders Company.)

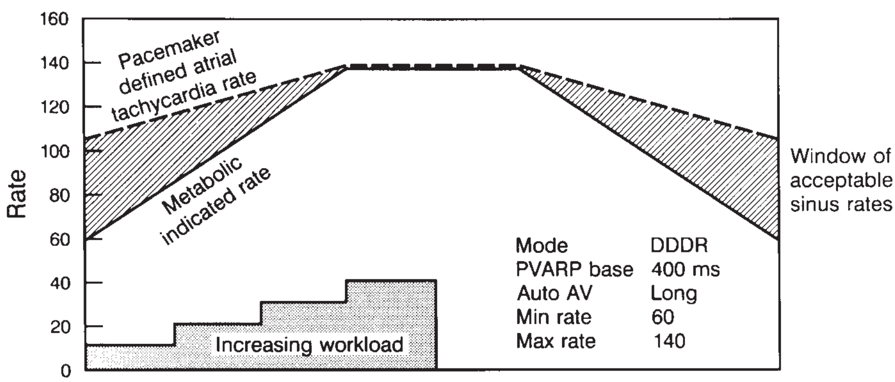


Figure 6.34. Diagram of the method by which a pacemaker monitors the atrial rate to determine whether it is physiologic or nonphysiologic. The shaded area identifies tracked sinus rates. Sinus rates below the metabolic indicated rate (*solid line*) elicit atrial pacing, sinus rates within the shaded area elicit atrial tracking, and sinus rates above the atrial tachycardia rate (*dashed line*) result in automatic switching of the mode to VVIR. Auto AV, automatic alteration of the AVI. (From Hayes DL, Ketelson A, Levine PA, et al. Understanding timing systems of current DDDR pacemakers. Eur JCPE 1993;3:70–86. By permission of Mayo Foundation.)

atrial events.[39] In most pacemakers, the rate at which mode switching occurs is a programmable feature. The pacemaker uses a counter that considers a short interval to be one that is shorter than the programmed mode-switching rate and a long interval to be one that is longer than the programmed rate. When the counter accrues a specified number of short intervals, the pacemaker reprograms to a nontracking mode and remains in this mode until a specified number of long intervals have occurred and altered the counter, at which point mode switching reverts. The nontracking mode to which the mode switch occurs may be a programmable option.

Variations on the mode-switching theme are too numerous to detail in this chapter. One should become familiar with the nuances of the mode-switching algorithms used.[40] Key to the implementation of mode switching is the pacemaker's ability to recognize high atrial rates. As discussed in the section on upper rate behavior, the TARP limits the atrial rate that can be detected and tracked. If rapid atrial rates are to be detected, identifying atrial events that occur during the refractory period is essential. In the modern dual-chamber pacemaker, this period includes the terminal portion of the AV delay and the latter portion of the PVARP. As noted for single-chamber refractory periods, the PVARP has absolute and relative portions. The absolute portion is the first part of the PVARP, and it is termed the *postventricular atrial blanking* (PVAB) period. The purpose of this timing period is to prevent sensing of the far-field R wave. The ventricular depolarization is a relatively large signal. To ensure sensing of pathologic atrial tachyarrhythmias whose signal amplitudes may fluctuate and may be very small, the atrial channel is usually programmed to a sensitive value. This combination predisposes to detection of ventricular signals on the atrial channel. The pacemaker may label these "P" waves and thus respond as if the atrial rate were high when the rhythm is actually normal sinus rhythm.[41–43] The result is a form of double counting, resulting in "false" mode switching. To prevent far-field R-wave sensing, a period of absolute refractoriness corresponding to the expected timing of this event forms the first portion of the PVARP. In devices with first-generation mode-switching algorithms, PVAB was not even mentioned because it was not programmable. In dual-chamber devices from virtually all manufacturers as of 2000, PVAB is programmable from 50 to 250 milliseconds. There is an inverse relationship between the duration of the PVAB and the detection of atrial arrhythmia, with the shorter PVABs allowing detection of higher atrial rates (increased sensitivity to atrial tachyarrhythmias). However, increasing the PVAB increases the specificity of rhythm detection and minimizes inappropriate mode switching.

Because a far-field R wave may be detected before the depolarization is sensed by the ventricular channel of the pacemaker (Fig. 6.35), another timing circuit, *preventricular atrial blanking* (pre-VAB), may be helpful. Although the site of native ventricular depolarization cannot be predicted, the algorithm sets up a monitoring interval following the detected atrial event. This programmable period varies from 0 to 60 milliseconds. If an R wave is detected during the pre-VAB interval, the atrial event is labeled a far-field R wave and is not used in the calculation of high atrial rates.

Atrial Flutter Response

An algorithm to specifically respond to atrial flutter is available in some pacemakers. Such an algorithm is designed to prevent pacing into the atrial vulner-

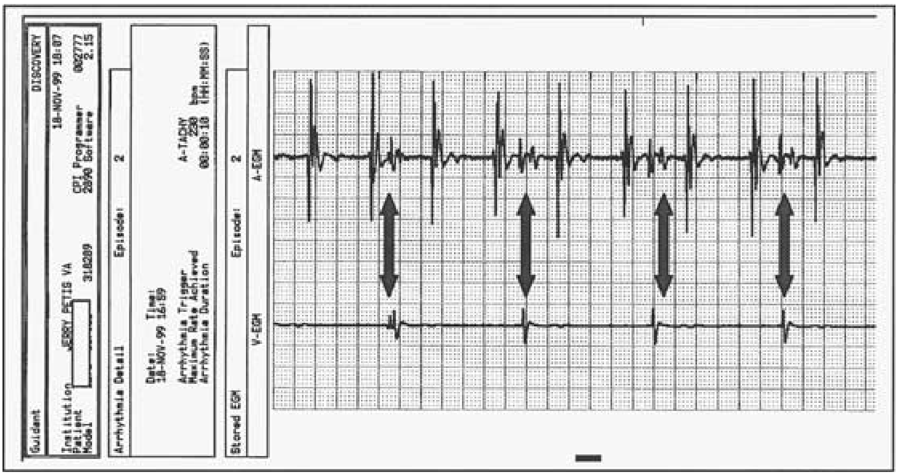


Figure 6.35. Stored electrogram from a pacemaker demonstrates mode-switching behavior (AV dissociation) during normal sinus rhythm with the pacemaker detecting an atrial rate higher than 200 bpm. The far-field R wave is identified by double arrows.

able period and to provide immediate fallback for atrial rates higher than the atrial flutter response (AFR) programmable rate. The fallback rate would be continued as long as atrial events continue to exceed the AFR programmable rate.[44,45]

For example, if the AFR were programmed to 250 bpm, an atrial event detected inside the PVARP or a previously triggered AFR interval would start an AFR timing window of 240 milliseconds (250 bpm). Atrial detection inside the AFR would be noted as "sensed" events within the refractory period and would not be tracked. The sensing window would begin only after both the AFR and the PVARP expire. If a paced atrial event is scheduled inside an AFR window, it is delayed until the AFR window expires (Fig. 6.36).

Sinus Preference

Another algorithm that may affect the timing cycle attempts to maintain sinus rhythm, i.e., sinus preference. The algorithm is programmed to search for the sinus rate, allowing a programmable number of beats per minute that the rate can be reduced as the search occurs. If sinus rhythm is detected within that programmable rate, the sinus rhythm is then allowed to predominate.[46]

Atrial Fibrillation Prevention Algorithms

Numerous atrial fibrillation prevention algorithms are available, and each of these may alter the pacemaker timing cycle. A complete discussion of these algorithms is beyond the scope of this chapter. Potential effects would include a shorter atrial pacing cycle after a premature atrial contraction to prevent the

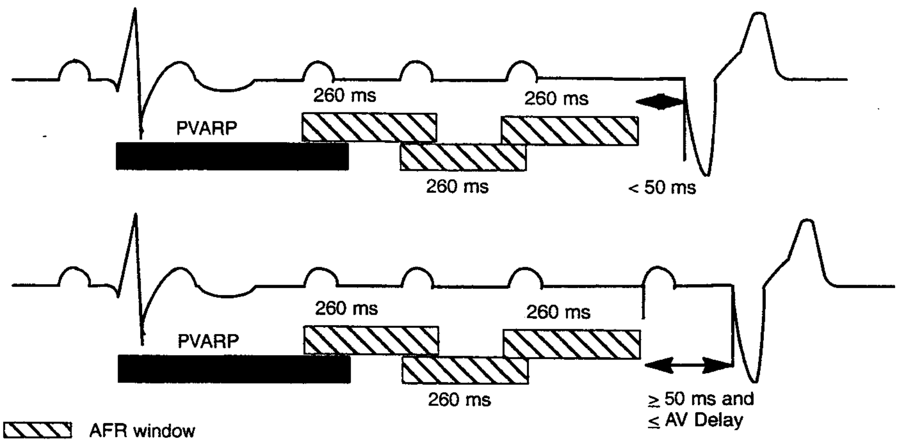


Figure 6.36. Artial Flutter Response. Atrial detection inside PVARP starts a 260-ms interval which will restart if another atrial event is detected. A ventricular pace will take place on the scheduled interval. An atrial pace will not occur unless there is at least 50 ms before the scheduled V pace. This prevents competitive pacing. (Courtesy of Guidant Corporation.)

"short-long" cycle that typically occurs, incremental atrial pacing rate to overdrive sinus rhythm and/or atrial premature contractions, and faster pacing following a mode switch episode.

Rate Smoothing and Ventricular Rate Regularization

Two additional algorithms may have an effect on the pacing rate and alter the rate from either the programmed lower rate, sinus-driven or sensor-driven rates. Rate smoothing, available for many years, is intended to prevent sudden changes in ventricular cycle length. Traditionally, rate smoothing operates between the LRL and the MTR (maximum pacing rate if in a single-chamber inhibited mode or DDI mode) in non–rate-adaptive pacing modes. Rate smoothing is programmable as a percentage, i.e., 3% to 24% in 3% increments, and can be programmed independently for increments and decrements in the paced rate. The pacemaker stores the most recent RR interval, whether intrinsic or paced, and uses this interval to calculate an allowable change in cycle length based on the rate smoothing percentage programmed. Figure 6.31 demonstrates rate smoothing.

Ventricular rate regularization (VRR) is a variant of rate smoothing. In patients with atrial fibrillation, the marked variation in RR intervals may, in part, be responsible for patient symptoms. VRR is used to minimize the cycle length variation during atrial fibrillation. It is similar to rate smoothing, with the exception that it may calculate the appropriate cycle length on the basis of a weighted sum of the current ventricular cycle length, as opposed to using the most recent ventricular cycle length with classic rate smoothing.[47]

Effect of Dual-Chamber Rate-Modulated Pacemakers on Timing Cycles

Dual-chamber rate-modulated (DDDR) pacemakers are capable of all the variations described for DDD pacemakers (see Fig. 6.14). In addition to using P-synchronous pacing as a method for increasing the heart rate, the sensor incorporated in the pacemaker may increase the heart rate. The rhythm may therefore be sinus driven (alternatively called "atrial driven" or "P synchronous") or sensor driven (Fig. 6.37).

An important difference in the timing cycle between DDD and DDDR pacing is the ability to pace the atrium during the PVARP in the DDDR mode (Fig. 6.38). This feature does not occur in the DDD mode, because paced atrial activity does not occur until the LRL has been completed, which, by definition, must be at some point after the PVARP. In the DDDR mode, however, even though the atrial sensing channel is refractory during the PVARP, sensor-driven atrial output can still occur (Fig. 6.38).[48]

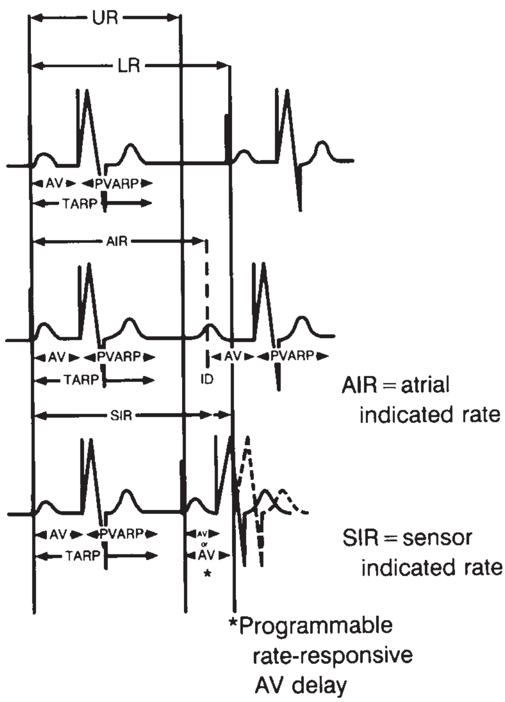


Figure 6.37. DDDR pacemakers are capable of all pacing variations previously described for DDD pacemakers (see also Fig. 6.14). When the device is functioning above the programmed LRL, it may increase the heart rate on the basis of the AIR or SIR. In most DDDR pacemakers, the PVARP remains fixed regardless of cycle length. Rate-adaptive or rate-variable AVI allows the length of the AVI to vary with the SIR; that is, as the SIR increases, the AVI shortens. Because an RRAVD is incorporated, the TARP may shorten by virtue of the changing AVI even though the PVARP does not change at faster rates.

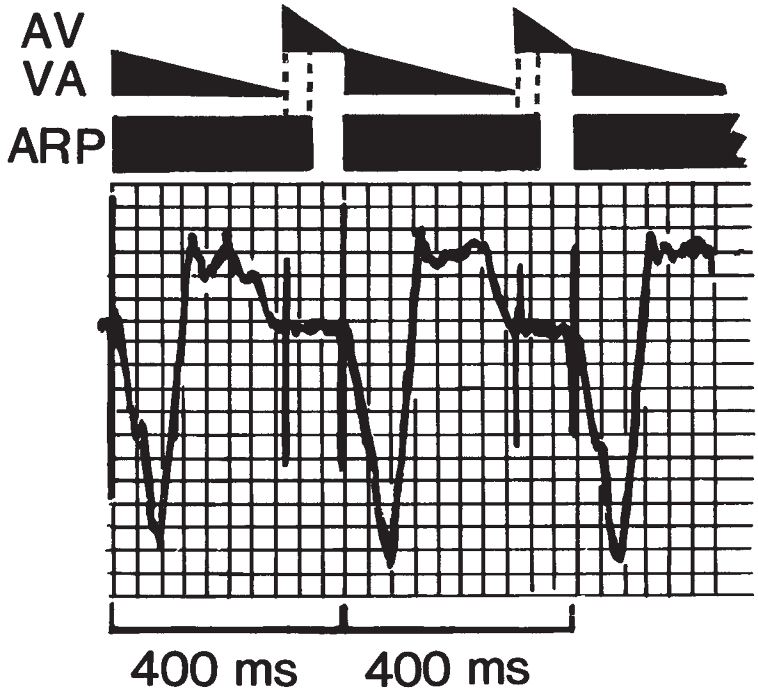


Figure 6.38. In this ECG example from a DDDR pacemaker, the MSR is 150 ppm (400 milliseconds), the ARP is 350 milliseconds, and the AVI is 100 milliseconds. As illustrated in the block diagrams above the ECG, the two sensor-driven atrial pacing artifacts both occur during the terminal portion of the PVARP. Even though no atrial sensing can occur during the PVARP, as can be seen in this example by the intrinsic P wave that occurs immediately after the first paced ventricular depolarization, a sensor-driven atrial pacing artifact is not prevented by the PVARP. Whether a sensor-driven atrial pacing artifact is delivered depends on the sensor-indicated rate at that time and not on the PVARP. (Reprinted by permission from Hayes DL, Higano ST. DDDR pacing: follow-up and complications. In: Barold SS, Mugica J, eds. New Perspectives in Cardiac Pacing, 2. Mount Kisco, NY: Futura, 1991:473–491.)

DDDR pacing systems further increase the complexity of the upper rate behavior. The pacemaker can be driven by intrinsic atrial activity to cause PV pacing or by a sensor with an input signal that is not identifiable on the ECG, or by both, to result in AV or AR pacing.[3,29] The eventual upper rate also depends on the type of sensor incorporated in the pacemaker and how the sensor is programmed.[49] Between the programmed LRL and the programmed URL, there may be stable P-wave synchronous pacing, P-wave synchronous pacing alternating with AV sequential pacing, or stable AV sequential pacing at rates exceeding the base rate (Fig. 6.39).[50] AV sequential pacing rates may increase as high as the programmed MSR.

Although the MSR and MTR are closely related, they are not identical. The tracking rate refers to the rate at which the pacemaker is sensing and track-

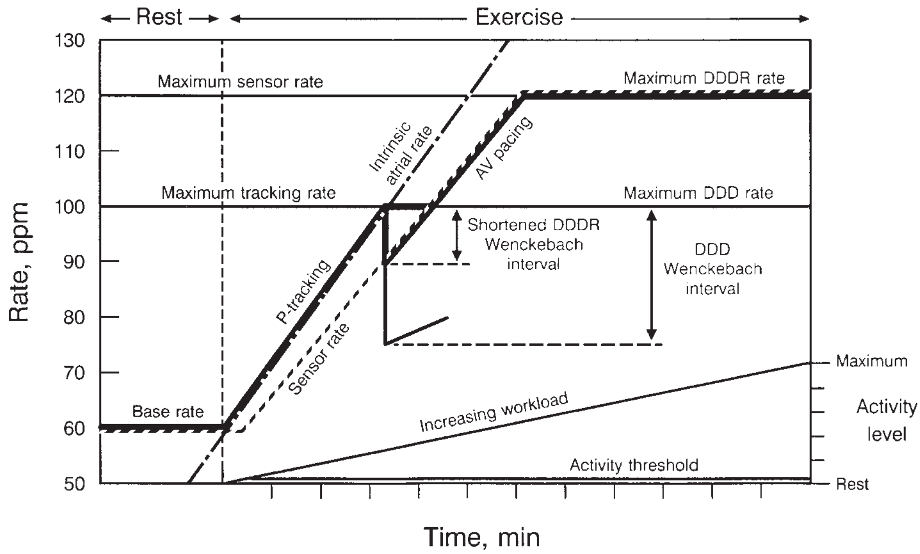


Figure 6.39. Diagram illustrating the rate response of the DDDR pacemaker and its behavior at both maximum tracking and the MSR. The *dashed-dotted line* represents the intrinsic atrial rate, and the *diagonal dashed line* represents the sensor rate during progressively increasing workloads. The *heavy black line* shows the ventricular paced rate, assuming complete heart block, as it progresses from the P-tracking mode to AV sequential pacing through a period of Wenckebach-type block. The DDD Wenckebach interval is shortened by sensor-driven pacing, that is, "sensor-driven rate smoothing." Maximum shortening of the Wenckebach period is accomplished by optimal programming of the sensor rate-response variables (threshold and slope programming for an activity-driven sensor). (From Higano ST, Hayes DL, Eisinger G. Sensor-driven rate smoothing in a DDDR pacemaker. Pacing Clin Electrophysiol 1989;12:922–929. By permission of Futura Publishing Company.)

ing intrinsic atrial activity. The MTR is the maximum ventricular paced rate that is allowed in response to sensed atrial rhythms. The MTR may result in fixed-block, Wenckebach, fallback, or rate-smoothing responses, depending on the design of the system. The sensor-controlled rate is the rate of the pacemaker that is determined by the sensor-input signal. The MSR is the maximum rate that the pacemaker is allowed to achieve under sensor control.

Whether at the MTR or during rate acceleration below the MTR, the rhythm that results may be in part sensor driven and in part sinus driven (P-wave tracking) and not purely one or the other (see Fig. 6.37). Which of these mechanisms predominates depends on the integrity of the sinus node and the sensor and how the pacemaker is programmed. DDDR pacing can result in a type of rate smoothing. If the sensor is optimally programmed, then as the atrial rate exceeds the MTR, the RR interval displays minimal variation between sinus-driven and sensor-driven pacing.[50] As shown in Figure 6.40, the variation in RR interval is markedly lessened with the sensor "on" (DDDR) rather than "passive" (DDD) mode. In the DDDR mode, the RR interval is allowed to lengthen only as much as the difference between the MTR and the activity sensor rate interval. For example, if a device is programmed to a P-wave tracking limit of 120 ppm and the patient's atrial rate exceeds this, then the pacemaker operates in a Wenckebach-type block. If the sensor-indicated rate at this time is 100 ppm, the paced rate decreases from 120 ppm (500 milliseconds) to an AV sequential paced rate of 100 ppm (600 milliseconds) for the Wenckebach cycle and then returns to P-wave tracking at a rate of 120 ppm. This situation usually shortens the DDD Wenckebach interval, but this interval depends on the atrial rate and the programmed values for the MTR and the TARP.

Maximal sensor-driven rate smoothing requires optimal programming of the sensor variable. If the rate-responsive circuitry is programmed to mimic the native atrial rate, the paced ventricular rate cannot demonstrate the 2:1 or Wenckebach-type behavior. Conversely, if the rate-responsive circuitry is programmed to low levels of sensor-driven pacing, little or no rate smoothing occurs (Figs. 6.39 and 6.41). Figure 6.40 shows the sensor "passive" (DDD)

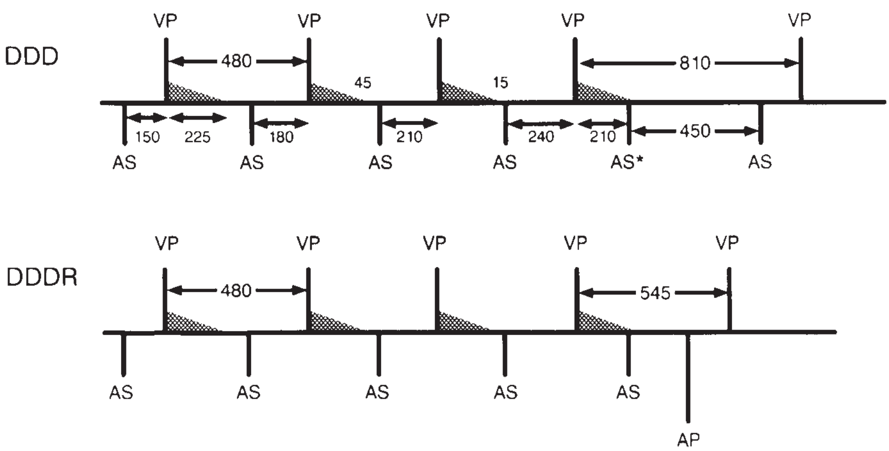


Figure 6.40. This diagram illustrates the difference in DDD and DDDR behavior when the intrinsic atrial rate increases. In the **upper panel**, DDD pacing is illustrated. The sensed atrial events (AS) occur increasingly closer to the PVARP, which is programmed to 225 milliseconds (shown by the shaded triangles) until the fifth AS event (*) occurs at 210 milliseconds after the preceding ventricular paced event (VP) and within the PVARP and is not sensed. This is followed by another AS and VP after the programmed AVI of 150 milliseconds. The resultant cycle length is 810 milliseconds, significantly longer than the preceding cycles of 480 milliseconds. In the **lower panel**, DDDR pacing is illustrated. The intervals are programmed to the same values as in the upper panel. When the fifth AS event occurs within the PVARP, it is, by definition, not sensed. However, the escape event is a sensor-driven atrial pacing artifact followed by a VP after the AVI. The sensor-indicated cycle length is 545 milliseconds. Therefore, only a 65-millisecond difference exists between the programmed URL and the sensor-indicated rate—a minor difference in cycle lengths. (Modified from Markowitz HT. Dual chamber rate responsive pacing [DDDR] provides physiologic upper rate behavior. PhysioPace 1990;4:1–4. By permission of Medtronic.)

response to exercise-induced increases in atrial rate, assuming complete heart block, an MTR of 100 ppm, and a Wenckebach-type response at the MTR. The ventricular and atrial rate responses to exercise are shown. As the MTR is exceeded, there is a transition from 1 : 1 P-synchronous function to Wenckebach upper rate behavior. Figure 6.39 shows the response that occurs with the sensor "on" (DDDR) and an MSR of 120 ppm. The ventricular rate response to exercise, along with the atrial and sensor rates, is shown. Below the maximum P-wave tracking rate, the ventricle is paced in a P-synchronous fashion, similar to sensor "passive" (DDD) function. However, with the sensor "on" (DDDR), there is a transition from P-synchronous to AV sequential pacing through a period of Wenckebach-type block as the atrial rate exceeds the MTR. The Wenckebach interval is shortened by sensor-driven pacing. The sensor rate response curve can be relocated almost anywhere on the graph by sensor parameter programming. Maximum sensor-driven rate smoothing requires optimal programming of these variables. Thus, sensor-modulated rate smoothing occurs only when the activity sensor is driving the pacemaker, when the intrinsic atrial rate exceeds the programmed MTR.

Another aspect of DDDR timing cycles is the ASW. The ASW is the portion of the RR cycle that is not part of the PVARP or the AVI. It is the

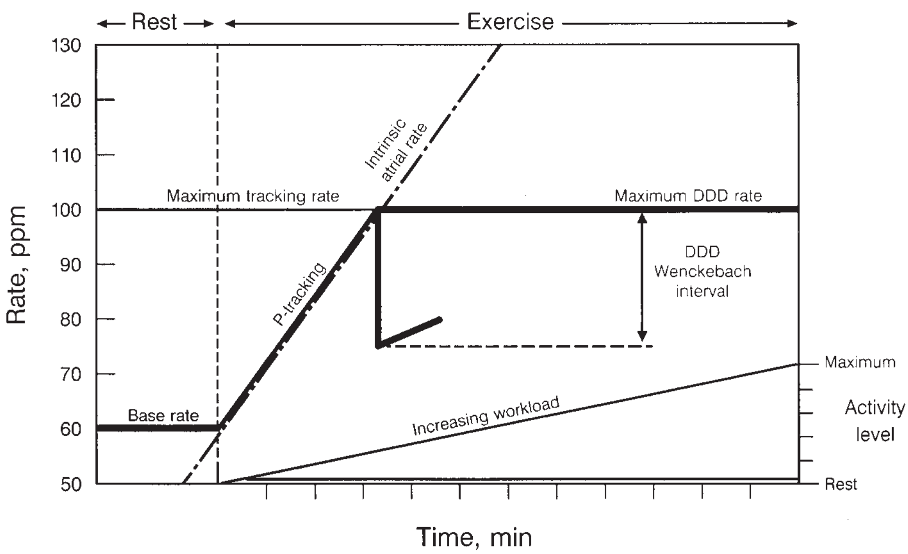


Figure 6.41. Diagram of the rate response of a DDD pacemaker with Wenckebach-type block at the URL (100 ppm). The *dashed-dotted line* represents the intrinsic atrial rate, and the *heavy black line* represents the ventricular paced rate, assuming complete heart block. The RR intervals during Wenckebach-type block vary as the atrial rate exceeds the MTR. (From Higano ST, Hayes DL, Eisinger G. Sensor-driven rate smoothing in a DDDR pacemaker. Pacing Clin Electrophysiol 1989;12:922–929. By permission of Futura Publishing Company.)

period during which the atrial sensing channel is alert. If the PVARP or AVI (or both) is extended, there may effectively be no ASW and even a DDD pacemaker functions as a DVI system. Conversely, if a DDDR pacemaker has exceeded the programmed MTR and is pacing at faster rates based on sensor activation, an appropriately timed intrinsic P wave can still inhibit the sensor-driven atrial pacing artifact and give the appearance of P-wave tracking at rates greater than the MTR (Fig. 6.42).[51] Although the MTR is programmed to a single value in DDDR pacing, it behaves as if it were variable and equal to the sensor-driven rate when the sensor-driven rate exceeds the programmed MTR

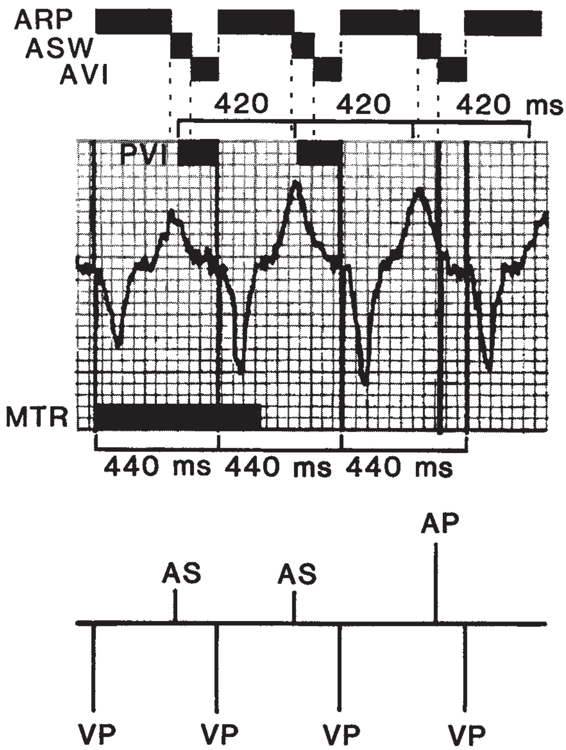


Figure 6.42. Diagram showing how an appropriately timed P wave can inhibit the sensor-driven A spike and result in apparent P-wave tracking above the MTR. In this example, the MTR is 100 ppm, or 600 milliseconds. The second and third complexes are preceded by intrinsic P waves that occurred during the ASW. This resulted in A-spike inhibition, or P-wave tracking above the MTR. The fourth complex was initiated by atrial pacing, because the preceding native P wave occurred outside the ASW in the ARP (ARP = 275 milliseconds). Note the short P-stimulus interval produced by the subsequent atrial spike. Also shown are the ASW (ASW = 65 milliseconds), AVI (AVI = 100 milliseconds), and variable PV interval (PVI). The intrinsic atrial rate is 143 bpm (420 milliseconds). The sensor rate is 136 ppm (440 milliseconds). A diagram in marker-channel fashion demonstrates the ECG findings. (From Higano ST, Hayes DL. P wave tracking above the maximum tracking rate in a DDDR pacemaker. Pacing Clin Electrophysiol 1989;12:1044–1048. By permission of Futura Publishing Company.)

if a P wave occurs during the ASW to inhibit output of an atrial pacing artifact.

Effects of Ventricular- and Atrial-Based Timing Systems on DDDR Timing Cycles

As noted previously, the "timing system" may affect the timing cycle. In a ventricular-based timing system, the effective atrial paced rate theoretically may be considerably higher than the programmed MSR if AR conduction were present (Fig. 6.43, top).[3] Assuming that the maximum sensor-controlled rate is 150 ppm (a cycle length of 400 milliseconds), the AEI with a programmed AVI of 200 milliseconds is also 200 milliseconds. If AV conduction were intact such that the AR interval was 150 milliseconds, the actual pacing interval would be ARI + AEI, or 150 + 200 milliseconds, or 350 milliseconds. A cycle length of 350 milliseconds equals 171 ppm, which is markedly higher than the programmed MSR of 150 ppm. Although this potentially achievable faster rate may not be a

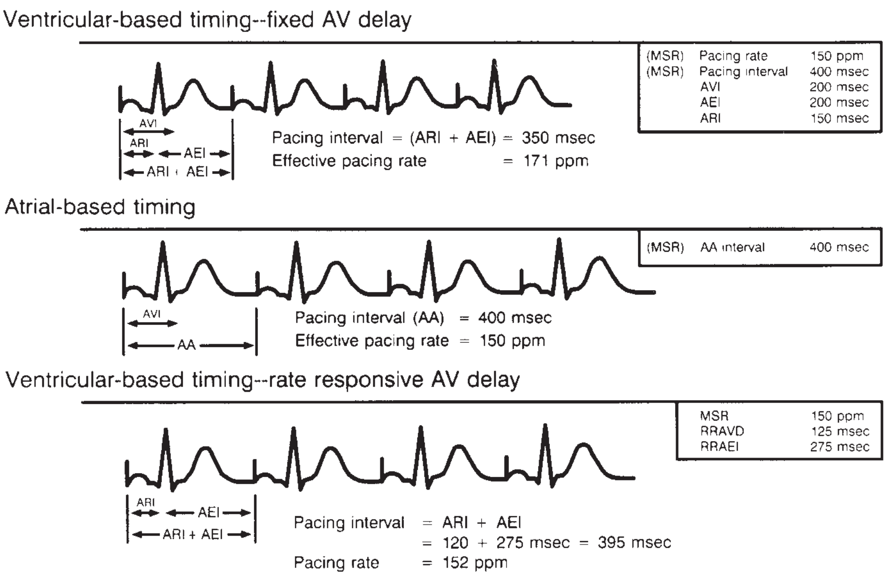


Figure 6.43. Effect of different timing systems on MSR with intact stable AV nodal conduction (AR pacing). **Top:** In a ventricular-based timing system, there is a considerable theoretical increase in the paced atrial rate exceeding that programmed by the physician. In the example shown, even though the MSR programmed is 150 ppm, or 400 milliseconds, the effective pacing rate achieved is 171 ppm, because the effective pacing rate is the sum of the ARI and the AEI; that is, 150 + 200 = 350 milliseconds (171 ppm). **Middle:** In an atrial-based system, the R wave sensed during the AVI alters the basic timing during stable AR pacing. This results in atrial pacing at the sensor-indicated rate. **Bottom:** The addition of an RRAVD to a ventricular-based timing system minimizes the increase in the paced atrial rate above the programmed sensor-indicated rate. (From Levine PA, Hayes DL, Wilkoff BL, Ohman AE. Electrocardiography of Rate-Modulated Pacemaker Rhythms. Sylmar, CA: Siemens-Pacesetter, 1990. By permission of Siemens-Pacesetter.)

problem or may even be advantageous for some patients, it could create problems for other patients (Fig. 6.43, middle).

Rate acceleration can also be minimized in a DDDR ventricular-based timing system by incorporating a rate-responsive AV delay (RRAVD).[29,52] As the sinus or sensor-driven rate progressively increases, RRAVD causes the PV and AVIs to progressively shorten (Fig. 6.43, bottom). Shortening the AVI with RRAVD results in a shorter TARP (shorter AVI + PVARP), which increases the intrinsic atrial rate that can be sensed and reduces the likelihood of both a fixed-block upper rate response and functional atrial undersensing. It also minimizes the chance of an inappropriately long PV interval at the higher rate, which may occur with a fixed AV delay when the fixed AV delay is programmed appropriately for lower rate behavior. In this case, the AV delay may be too long at higher rates. In a DDDR system, when the AVI shortens, the ventricular rate drive is held to that governed by the sensor so that the time subtracted from the AVI is added to the AEI. Thus, at a rate of 150 ppm and pacing interval of 400 milliseconds, if the RRAVD causes the AVI to shorten by 75 milliseconds from an initially programmed AVI of 200 milliseconds, then the AVI shortens to 125 milliseconds. Because the overall ventricular timing is held constant, the 75 milliseconds subtracted from the AVI is added to the AEI, increasing it to 275 milliseconds.

The RRAVD provides a more physiologic AVI at the faster rate and minimizes the degree of rate increase over the programmed MSR if AR conduction is intact. Assuming that the rate is 150 ppm and the initial AVI is 200 milliseconds, the RRAVD is 125 milliseconds, resulting in AV sequential pacing at the sensor programmed rate when the AR interval is 140 milliseconds. If intact AV conduction is present at 120 milliseconds, the overall shortening of the pacing interval is only 5 milliseconds more than that seen at 150 bpm, a rate of 152 bpm (Fig. 6.43, bottom).

Another option is extending the VAI as needed to control the AA pacing rate according to the programmed MSR (Fig. 6.44). This extension results in adaptive-rate pacing, regardless of AV conduction status, which is equal to, but does not exceed, the desired MSR.

ENDLESS-LOOP TACHYCARDIA

Endless-loop tachycardia (ELT) is not a portion of the timing cycle, but understanding the timing cycle of dual-chamber pacing is crucial to understanding ELT, and vice versa. ELT has also been referred to as "pacemaker-mediated tachycardia" (PMT), "pacemaker-mediated reentry tachycardia," and "pacemaker circus movement tachycardia."[9] ELT has been defined as a reentry arrhythmia in which the dual-chamber pacemaker acts as the anterograde limb of the tachycardia and the natural pathway acts as the retrograde limb.[53,54]

If AV synchrony is uncoupled—that is, if the P wave is displaced from its normal relation to the QRS complex—the subsequent ventricular event may result in retrograde atrial excitation if retrograde or VA conduction is intact.[53,54]

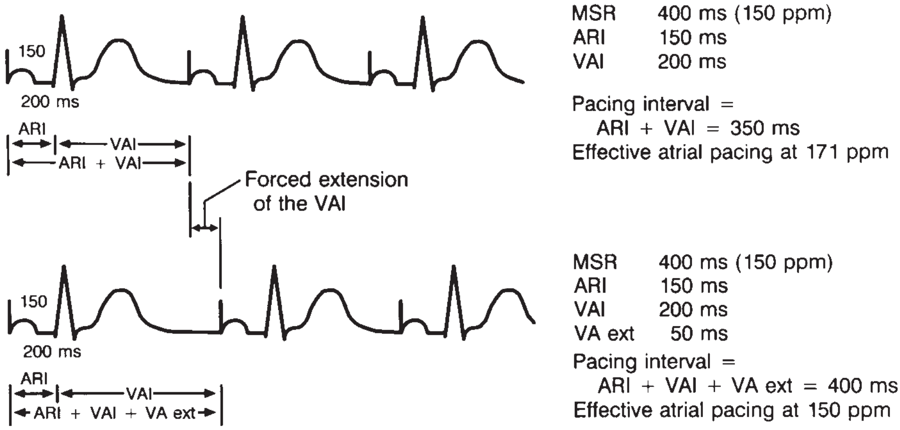


Figure 6.44. Pacing at MSR. Timing algorithm provides effective pacing at MSR with intrinsic conduction to the ventricle. ARI = interval from atrial stimulus to sensed R wave; VA = ventriculoatrial; VAI = ventriculoatrial interval. (From Hayes DL, Ketelson A, Levine PA, et al. Understanding timing systems of current DDDR pacemakers. Eur JCPE 1993;3:70–86. By permission of Mayo Foundation.)

If the retrograde P wave is sensed, the AVI of the pacemaker is initiated. On termination of the AVI and MTR interval, a ventricular pacing artifact is delivered, which could once again be conducted in a retrograde fashion. Once established, this reentrant mechanism continues until interrupted or until the retrograde limb of the circuit is exhausted. The paced VV interval cannot violate the programmed maximum or URL of the pacemaker, and the ELT often occurs at the URL. Many mechanisms have been adopted to prevent or minimize ELT.[55]

Among the early preventive algorithms was automatic PVARP extension following a PVC, because ventricular ectopic beats were the most common triggers for an ELT. ELT was not a major problem when the programmed base rate was low; however, if the base rate is intentionally programmed to a relatively high level or is functioning there due to sensor drive, PVARP extension blocks detection of either a retrograde or an anterograde P wave. Because of the high rate, however, the AEI may time out, resulting in delivery of an atrial output pulse when the atrial myocardium is still refractory from the native depolarization. In this circumstance, atrial output is ineffective. If the patient can sustain retrograde conduction, this sequence of events can result in a rhythm termed *repetitive nonreentrant ventriculoatrial synchrony*.

Algorithms for Termination of Pacemaker-Mediated Tachycardia

If ELT cannot be prevented, various recognition and termination algorithms are available. The simplest algorithm assumes that atrial-sensed ventricular pacing occurring at the MTR is a PMT and after a preset number of cycles either withholds ventricular output or extends the PVARP. If the rhythm is a true ELT, it is terminated by this mechanism. A further refinement to these algorithms allows the clinician to select an ELT rate that is below the MTR. This adjustment addresses the balanced ELTs in which the sum of the retrograde conduction (VA) interval plus the sensed AV delay is longer than the MTR interval, and, hence, the ELT rate is slower than the MTR. The limitation of both these algorithms is that they respond whether the rhythm is an ELT or an intrinsic atrial rhythm that is being appropriately tracked by the pacemaker. For a native atrial rhythm, repeated pauses are caused by the activation of the PMT termination algorithm.

Another approach is to monitor the retrograde conduction interval. If the VP interval is stable, the device labels the rhythm as a possible PMT and then varies the next PV interval. If the atrial rhythm is independent of the ventricular paced event, the VP interval on the next cycle is either lengthened or shortened by the same degree that the PV interval was changed. The rhythm is then labeled normal, and normal atrial synchronous ventricular pacing continues. If the VP interval is stable, the P wave was caused by retrograde conduction (related to the ventricular paced event), and the rhythm is probably a PMT. At that point, ventricular output is withheld following the detected P wave. An atrial alert period is initiated, and if another P wave is not detected, an atrial output pulse is delivered 330 milliseconds later. This interval was chosen as sufficient for recovery of the atrial myocardium. Successful atrial capture breaks the cycle and prevents retrograde conduction after the next ventricular paced complex. This algorithm also prevents some of the pauses occurring with an earlier generation of PMT algorithms (Fig. 6.45).

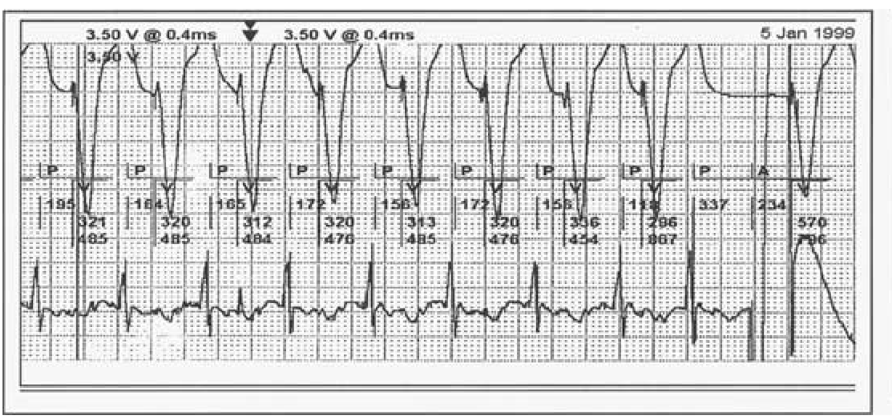


Figure 6.45. Endless-loop tachycardia was induced during an atrial capture threshold test (loss of atrial capture allowed for retrograde conduction). The PMT algorithm was enabled. The PV interval was shortened; the subsequent VP interval was stable, resulting in withholding of ventricular output and delivery of atrial output 330 milliseconds later.

Noncompetitive Atrial Pacing

Noncompetitive atrial pacing (NCAP) is used to minimize competition between the sensor (atrial pacing) and sinus rhythm. Implementation of this capability has been facilitated by microprocessors and the ability of pacemakers to detect events coinciding with the refractory period. If atrial depolarization is sensed within the alert period, it inhibits atrial output and triggers ventricular output. However, if the native atrial event coincides with the PVARP, it may be detected but does not otherwise alter the basic timing period of the pacemaker. With NCAP enabled, if atrial output is scheduled to be delivered within a given interval after the detected P wave, atrial output is delayed until a preset interval has timed out. A Medtronic device, for example, uses a fixed interval of 300 milliseconds (this may not always be sufficient, in our experience). Atrial output is delivered at that time. To maintain a stable ventricular rate, the paced AVI may be foreshortened for this one cycle (Fig. 6.46).

SUMMARY

A clear understanding of the components of pacemaker timing cycles is crucial to understanding and interpreting paced ECGs. The information in this chapter provides basic rules for timing cycles for pacing modes currently in use (VVI, AAI, VVIR, AAIR, DDI, DDD, DDDR, DDIR) and for pacing modes less fre-

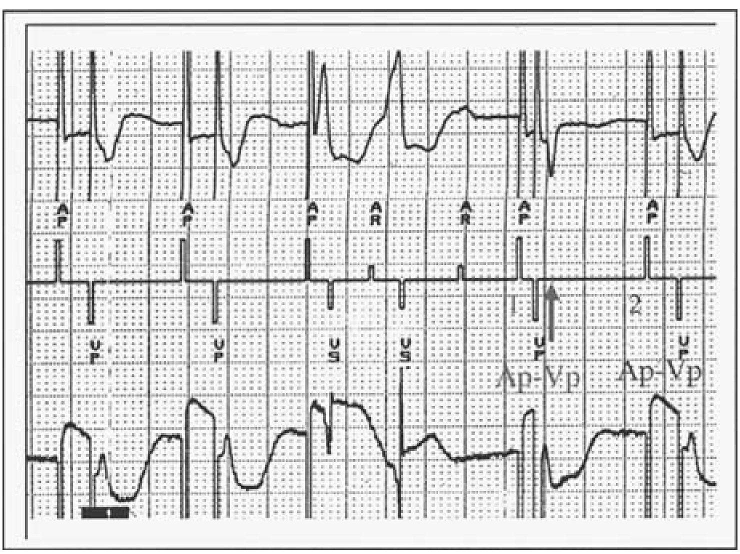


Figure 6.46. Premature ventricular contraction associated with a retrograde P wave. This P wave coincides with the PVARP and is not tracked. But it is sensed and labeled "AR." The scheduled atrial output is delayed 300 milliseconds. This results in a foreshortening of the AV delay. AP = atrial paced event; AS = atrial sensed event; VP = ventricular paced event; VS = ventricular sensed event. (Courtesy of S. Serge Barold, M.D.)

quently used or of historical interest but still important to understand how timing cycles have developed (VOO, AOO, DOO, DVIC, DVI, VDD).

Each pacemaker manufacturer may take license and alter or add some nuance to the timing cycle of a particular pacemaker. Although understanding basic timing cycles allows interpretation of most paced ECGs, manufacturers' alterations require familiarity with the design of each pacemaker to be interpreted. When unexpected behavior of the pacemaker occurs in a patient whose condition is clinically stable, the presumption should be that this reflects a unique behavioral eccentricity of the pacemaker. All manufacturers maintain a group of technical service engineers who are available 24 hours a day, 7 days a week. They should be contacted before any intervention, such as replacing the pulse generator, is attempted, for in all probability the device is behaving normally.

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