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Loss of electrical ventricular resynchronization in biventricular pacemakers

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Ventricular resynchronization for congestive heart failure (CHF) with biventricular pacing has increased the complexity of device programming and follow-up by virtue of additional timing cycles [1–7]. Ventricular resynchronization devices that memorize episodes of ventricular sensing together with preceding events have facilitated the diagnosis of loss of resynchronization [1, 2]. The long-term stored data in resynchronization devices are diagnostically far superior than conventional 24 h Holter recordings. Although the term "ventricular resynchronization" describes the mechanical effect of biventricular pacing, the term is used in this discussion to describe biventricular pacing which is an electrical event and should not be automatically equated with the presence of mechanical synchrony. The term "desynchronization" describes the opposite electrical phenomenon — loss of biventricular pacing. Furthermore, the well-known problem of double counting of the ventricular electrogram by first-generation biventricular pacemakers will not be addressed in this discussion [8].

The following abbreviations are used in the text: AS — atrial sensed event, AP— atrial paced event, AR — atrial event sensed in the pacemaker atrial refractory period (where it cannot initiate a programmed AV delay), VS — ventricular sensed event, VP — ventricular paced event.

Upper rate response of biventricular pacemakers

Correct programming of the upper rate response of biventricular pacemakers is important for maintaining ventricular resynchronization at all times. It is therefore essential to recognize upper rate behavior that reduces the "dose" of ventricular resynchronization and correct it by reprogramming [1–7].

The upper rate response of biventricular pacemakers differs from the traditional Wenckebach or fixed-ratio upper rate response of conventional antibradycardia pacemakers because congestive heart failure (CHF) patients generally do not have significant sinus bradycardia or AV junctional conduction delay despite beta-blocker therapy.

The upper rate response of biventricular pacemakers exhibits 2 forms according to the location of the P wave in the pacemaker cycle:
- a pre-empted Wenckebach upper rate response with AS-VS sequences and the P wave (tracked) beyond the postventricular atrial refractory period (PVARP);
- AR-VS sequences with the P wave sensed (but not tracked) within the PVARP (Table 1) [2].

Pre-empted Wenckebach upper rate response

In a traditional Wenckebach upper rate response of a DDD pacemaker, the device (where upper rate interval must be longer than the total atrial refractory period) delivers its ventricular stimulus only at the completion of the (atria- driven) upper rate interval. The AV delay initiated by a sensed P wave increases progressively because the ventricular channel is compelled to deliver its stimulus at the completion of the programmed upper rate interval. Eventually a P wave falls in the PVARP, a pause occurs and the ventricular paced sequence (group beating) repeats itself. In patients with a biventricular pacemaker, the Wenckebach upper rate response (or more precisely the manifestation of upper rate > total atrial refractory period) may not

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Table 1. Comparison of the two types of upper rate response of biventricular pacemakers in patients with normal sinus node and AV conduction.

	Wenckebach block	**Atrial refractory block**
VS-VS interval	< URI	< URI and < TARP
P wave sensing	All P waves are sensed beyond the PVARP	All P waves are unsensed (not tracked) in the PVARP where they cannot initiate a programmed AV delay.
PR interval	AS-VS > programmed AS-VP	AR-VS > programmed AS-VP
Ventricular pacing during established response	No	No
Entry	1. Gradual prolongation of AV delay (AS-VP) to the duration of the spontaneous PR interval (AS-VS). 2. During the above, ventricular pacing contributes progressively less to ventricular fusion with the spontaneous QRS complex until ventricular pacing is inhibited by VS-VS sequences < URI.	1. Occurs when URI = TARP (W = 0) without intervening Wenckebach block. 2. Occurs following Wenckebach block when the P-P interval < TARP. Will not occur if TARP is short (W long).
Progression with increase in atrial rate	1. No change will occur if Wenckebach interval is long. AS-VS sequences continue and zone of refractory block will not be reached. 2. Wenckebach sequence may change into refractory block if Wenckebach interval is short and atrial rate > TARP or P-P interval < TARP.	Remains unchanged but if the PR is long, AR may eventually move into the PVAB whereupon no AR marker will be registered.
Markers	AS-VS, AS-VS, AS-VS All P waves are followed by a spontaneous (conducted) QRS complex.	AR-VS, AR-VS, AR-VS All P waves are followed by a spontaneous (conducted) QRS complex.
Exit	During exit at the URI, ventricular pacing occurs with progressively more contribution to fusion with the spontaneous QRS complex until pure ventricular pacing supervenes. AS-VP sequences occur just below the programmed upper rate.	AS-VP sequences do not return when the P-P interval drops just below the programmed TARP [(AS-VP) + PVARP]. AS-VP sequences return when the P-P interval drops below the longer prevailing TARP [(AR-VS) + PVARP] because AR-VS > AS-VP.
Transient ventricular pacing	Briefly during entry and briefly during exit from established sequence	No

P-P interval — interval between 2 sinus P waves, AS — atrial sensed event, AP — atrial paced event, AR — atrial event sensed in the atrial refractory period, VS — ventricular sensed event, VP — ventricular paced event, PVARP — postventricular atrial refractory period, PVAB — postventricular atrial blanking period, TARP — total atrial refractory period, URI — upper rate interval, W — Wenckebach interval, URI – TARP = maximal extension of the AV delay during a Wenckebach upper rate response (maximal AV delay = programmed AV delay + W) (Reproduced with kind permission of Springer Science and Business Media [2]).

be immediately recognizable because no paced beats are evident.

In patients with normal or near normal sinus node function and AV conduction and a relatively short PVARP, the Weckenbach upper rate response of a biventricular pacemaker creates a repetitive pre-empted process in the form of an attempted Wenckebach upper rate response with each cycle. There is a partial or incomplete extension of the programmed AV (AS-VP) interval in each pacemaker cycle but the device cannot release VP because the conducted spontaneous QRS complex continually occurs before completion of the upper rate interval when VP is expected [1, 2, 9]. The spontaneous QRS complex is therefore sensed by the pacemaker, and ventricular pacing is pre-empted. In other words, the pacemaker cannot time out the full extended AV delay and the full upper rate interval and thus, it cannot emit a ventricular stimulus (Figs. 1, 2). This form of upper rate response tends to occur in patients with relatively normal AV conduction, a short programmed AV delay, a relatively slow programmed (atrial-driven) upper rate, and a sinus rate faster than the programmed (atrial-driven) upper rate. It is therefore more likely to emerge on exercise or during times of distress

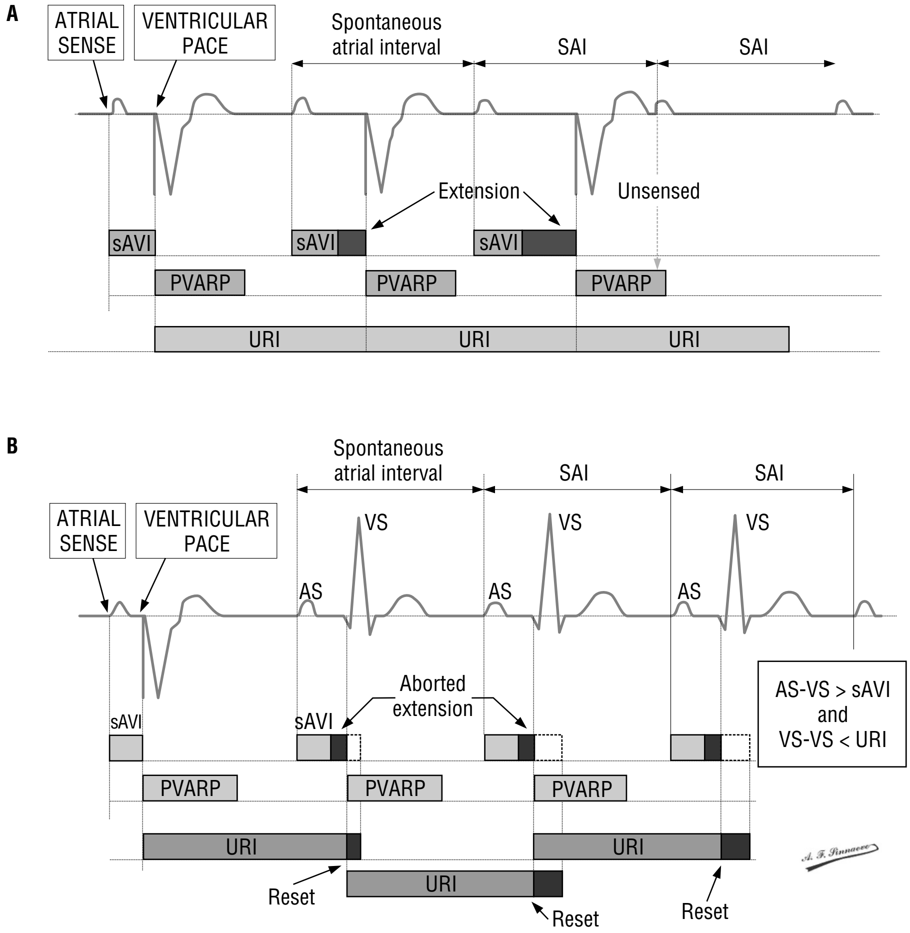

Figure 1. **A.** Normal pacemaker Wenckebach upper rate response. **B.** Repetitive pre-empted Wenckebach upper rate response. AS — atrial sensed event, VS — ventricular sensed event, VP — ventricular paced event, PVARP — postventricular atrial refractory period, URI — upper rate interval, sAVI — sensed AV delay initiated by atrial sensing, AV — atrioventricular, SAI — spontaneous atrial interval. See text for details (Reproduced with permission from: Barold SS, Stroobandt RX, Sinnaeve AF. Cardiac pacemakers step by step. An illustrated guide. Blackwell--Futura, Malden MA 2004).

when adrenergic tone is high. The occurrence of a pre-empted Wenckebach response defeats the very purpose of this type of cardiac stimulation in heart failure patients. Because patients with CHF are susceptible to sinus tachycardia (especially during decompensation despite beta-blocker therapy), it is particularly important to program a relatively fast upper rate during biventricular pacing to avoid an upper rate response manifested by the emergence of the patient's spontaneous conducted QRS complex.

Upper rate limitation with P wave in the PVARP: atrial refractory block

In a conventional antibradycardia pacemaker, as the atrial rate increases, a so-called fixed-ratio upper rate response follows a traditional Wenckebach upper rate response. A fixed-ratio response occurs when the sinus or P-P interval ≤ the total atrial refractory period (TARP) < programmed upper rate interval or URI (or when P-P interval ≤ URI = TARP), and it often takes the form of 2:1 block where every alternate P wave is located in the PVARP where it cannot initiate a programmed AS-VP interval. When P-P interval < TARP during biventricular pacing (in the setting of relatively normal sinus node function and AV conduction), a 2:1 block response does not usually occur because every spontaneous P wave falls in the PVARP (depicted in the marker channel as a atrial event sensed in the pacemaker refractory period) where they cannot be tracked (or initiate the programmed AS-VP interval). The conducted QRS complex (VS) linked to the preceding P wave (in the PVARP) initiates a PVARP that will contain the succeeding P wave. This sequence ensures the perpetuation of functional atrial undersensing [1, 2] (Fig. 3).

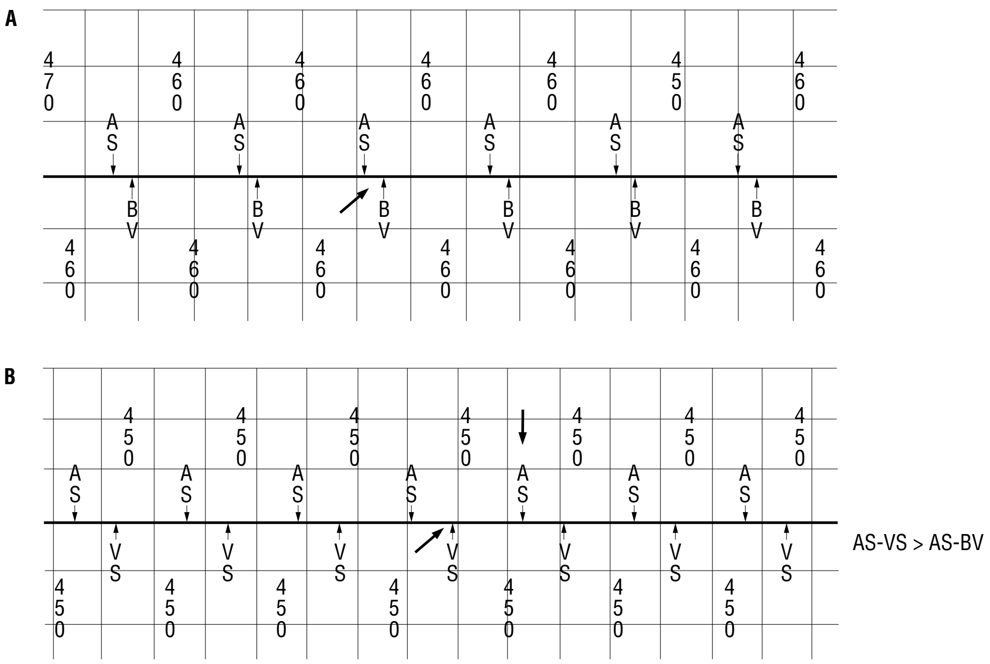

Figure 2. Stored markers from a Medtronic InSync II Marquis biventricular ICD showing the development of a pre-empted Wenckebach upper rate response during biventricular pacing. Upper rate interval (URI) = 460 ms. **A.** There is 1:1 atrial tracking and biventricular (BV) pacing with the programmed AS-VP delay. **B.** When the spontaneous ventricular rate exceeds the programmed upper rate (VS-VS < URI), a pre-empted Wenckebach upper rate response supervenes. AS conducts to VS so that AS-VS becomes longer than the programmed AS-VP interval. Note that the sinus P wave is sensed beyond the PVARP and that there is absence of pacemaker stimuli or pauses typical of a traditional Wenckebach upper rate response. AS — atrial sensed event, VS — ventricular sensed event, BV — biventricular pacing event, VP — ventricular paced event, PVARP — postventricular atrial refractory period. The displayed interval durations by the programmer are approximate (Reproduced with kind permission of Springer Science and Business Media [2]).

Thus, no P wave can be tracked (Table 1). In this situation, the prevailing AV delay (or the spontaneous PR interval or AR-VS) is longer than the programmed AS-VP. There are no pauses and no pacemaker stimuli are evident as in the pre-empted Wenckebach upper rate response.

Exit from upper rate response and restoration of P wave tracking

When the upper rate response pushes the P wave into the PVARP with resultant loss of ventricular resynchronization, a biventricular pacemaker may not resume 1:1 atrial tracking when the sinus rate drops just below the programmed upper rate [1–5]. The P wave can remain in the PVARP even when the P-P interval is longer than the upper rate dictated by the programmed TARP (Fig. 4). The TARP is the sum of the programmed (AS-VP + PVARP). This behavior is simply the response to the fact that AR-VS (spontaneous AV conduction or PR interval) is longer than the programmed AS-VP interval (Fig 4). Based on the different durations of the AV delay, the TARP during AR-VS operation [(AR-VS) interval + PVARP] must therefore be longer than the programmed TARP [(AS-VP) interval + PVARP]. The pacemaker will continue to operate with desynchronized AR-VS cycles below the upper rate (dictated by the programmed TARP) until the P-P or sinus interval becomes longer than the sum of (AR-VS) interval + PVARP thereby allowing escape of the trapped sinus P wave out of the PVARP (Fig. 4). Thus, restoration of resynchronization will occur at a rate slower than the programmed upper rate (dictated by the programmed TARP). These considerations are important in CHF patients who may occasionally develop substantial increases in sinus rates despite beta-blocker therapy.

The postponed restoration of atrial tracking upon emergence from the upper rate is worse in patients with first-degree AV block. For example, with intrinsic AV conduction of 300 ms and a PVARP programmed to 310 ms, the atrial rate must fall below 100 bpm before atrial tracking is

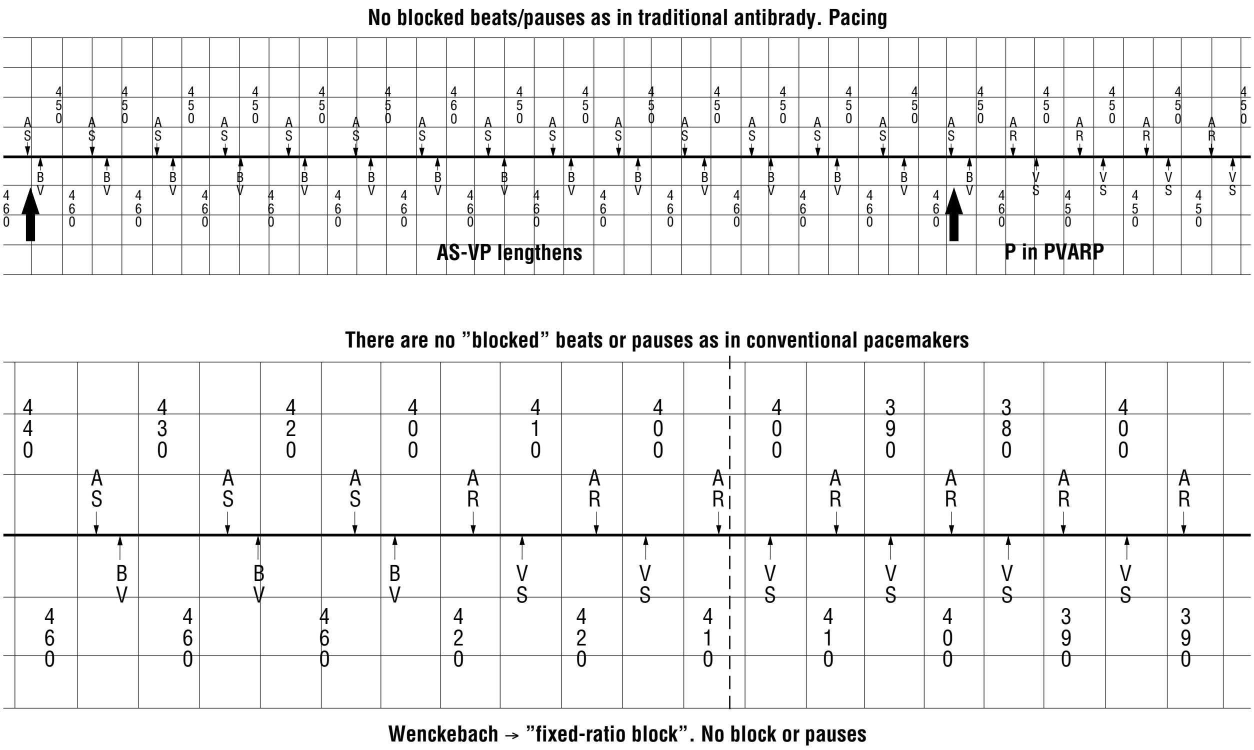

Figure 3. Upper rate response in stored markers recorded from a Medtronic InSync II Marquis biventricular ICD. There is a typical Wenckebach upper rate response (with progressive prolongation of the AS-VP interval) which terminates with a sequence of atrial refractory block consisting of AR-VS combinations where the sinus P wave is in the PVARP and is not being tracked. The P wave conducts to the ventricle. Note the absence of pacemaker stimuli or pauses typical of traditional Wenckebach, and "fixed-ratio" upper rate responses. AS — atrial sensed event, AR — atrial sensed event in the pacemaker atrial refractory period, VP — ventricular paced event, VS — ventricular sensed event, PVARP — postventricular atrial refractory period (Reproduced with kind permission of Springer Science and Business Media [2]).

restored, thereby resuming resynchronization delivery. A similar situation was seen with first-generation biventricular devices because of double ventricular counting where 1: 1 atrial tracking (AS-VP pacing) returned only when the sinus interval became longer than [AR-VS] interval + PVARP + ICD (ICD — interventricular conduction delay or the interval between the right ventricular (RV) and left ventricular (LV) electrograms both sensed by the common sensing channel of these device) [5, 8].

Programming the upper rate

Inappropriately low upper rates in patients with normal sinus and AV nodal function is an important cause of ventricular desynchronization that can deny patients the benefit of resynchronization at high atrial rates which are not uncommon in this patient population during exercise or situations associated with increased circulating catecholamines (especially during decompensation despite beta-blocker therapy) [1, 3–7]. Relatively low upper rates must also be avoided even in patients with symptomatic angina because loss of resynchronization can itself precipitate cardiac ischemia by increasing MVO_2. Loss of ventricular resynchronization at high sinus rates can be reduced or prevented by programming a relatively high pacemaker upper rate because the risk of tracking rapid atrial rates by the implanted device (as with antibradycardia pacemakers) is not an important issue in the presence of normal AV conduction. However, the programmable values of the upper rate may be restricted in biventricular ICDs by the programmed maximum ventricular tachycardia interval to be detected.

Programming a fast upper rate may be difficult in some patients with retrograde ventriculoatrial conduction where more "squeezing" of the AV delay to shorten the TARP may cause unfavorable hemodynamics. Alternatively, the maximum spontaneous rate could be attenuated by larger doses of beta-blockers (often better tolerated with device therapy [10]) or other drugs that depress sinus node function. In difficult or refractory

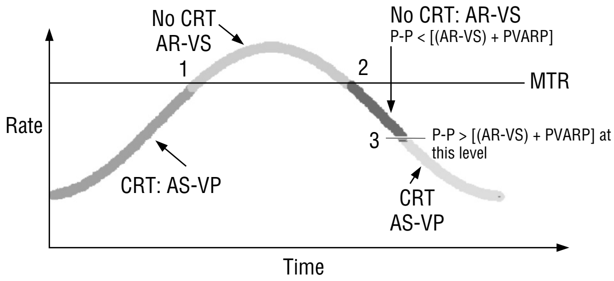

Figure 4. Diagram showing an upper rate response with the P wave falling within the postventricular atrial refractory period (PVARP) in the setting of normal AV conduction. Ventricular resynchronization occurs with AS-VP sequences (as programmed) when the sinus rate is below the maximum tracking rate (MTR). When the atrial rate exceeds the MTR at point 1, the P wave falls within the PVARP (sensed in the atrial refractory period and depicted by the AR marker) and ventricular resynchronization is lost. The spontaneous rhythm takes over with AR-VS sequences and AR conducting to the ventricle (depicted by VS). When the sinus rate falls below the MTR at point 2, ventricular resynchronization does not occur because the timing cycles of the device force the continuation of AR-VS sequences. Failure of ventricular resynchronization at this stage results from the longer prevailing total atrial refractory period (TARP) which is equal to [(AR-VS) + PVARP] which is longer than the programmed TARP = [(AS-VP) + PVARP] simply because AR-VS > AS-VP. Ventricular resynchronization with AS-VP sequences is restored at point 3 when the sinus or atrial interval (P-P) > [(AR-VS) + PVARP], at a sinus rate substantially lower than the MTR. AS — atrial sensed event, VS — ventricular sensed event, VP — biventricular paced event, AR — atrial event sensed in the atrial refractory period of the pacemaker where tracking cannot occur, AV — atrioventricular, PVARP — postventricular atrial refractory period, CRT — cardiac resynchronization theraphy (Reproduced with permission from [1]).

cases, ablation of the AV junction should be considered to ensure continual ventricular depolarization by the implanted device.

Loss of resynchronization below the programmed upper rate: Locking of P waves in the PVARP

Desynchronized AR-VS, AR-VS… sequences containing trapped or locked P waves within the PVARP can also occur outside of situations where a fast atrial rate (> the programmed upper rate) gradually drops below the programmed upper rate as discussed above [1–6]. There are many causes of desynchronization that can start at rates slower than the programmed upper rate (Table 2). For example, during sinus rhythm and synchronized biventricular pacing (below the upper rate), a ventricular premature complex (or T wave oversensing which produces the same effect) (Figs. 5, 6) by initiating a regular PVARP, shifts pacemaker timing so that the succeeding undisturbed sinus P wave now falls in the PVARP. This P wave within the PVARP conducts to the ventricle producing a spontaneous QRS complex sensed by the device. The sinus P waves will remain trapped in the PVARP as long as the P-P interval < [(AR-VS) + PVARP]. In other words, biventricular pacing remains inhibited until either the occurrence of a non-refractory sensed atrial depolarization or delivery of an atrial pacing pulse outside the TARP. Loss of atrial synchrony may extend over a period of time (e.g., seconds to hours) depending on the pacemaker's programmed rate settings and the patient's sinus rate. These forms of ventricular desynchronization (AR-VS sequences) may be symptomatic, not uncommon and can be precipitated by a variety of mechanisms (Table 2) [1, 3–6].

Similarly, an undersensed atrial event that conducts, resulting in an R-wave that is a "pacemaker-defined" premature ventricular complex may cause the next atrial event to occur during a PVARP and bring about a second conducted R-wave. The AR-VS pattern may continue if the patient's atrial rate is fast enough.

Events that may disrupt AV synchrony include ventricular premature complexes, atrial premature complexes, T wave oversensing, noise sensing and associated asynchronous pacing, also known as "noise reversion" etc.

Factors influencing the development of desynchronization

The development of ventricular desynchronization is favored by a relatively fast sinus rate (but below the programmed upper rate), first-degree AV block and a relatively long PVARP (Fig. 7). In modern dual chamber pacemakers, the programmed initial PVARP may vary as a function of the heart rate or sensor rate. In the context of these types of pacemakers, the relatively long PVARP that may be in effect at lower rates can result in persistent loss of AV synchrony.

An atrial tachyarrhythmia may often result in an AR-VS pattern with a rate faster than the upper tracking rate (UTR). If the tachyarrhythmia breaks with the atrial rate slowing below the UTR, the first atrial depolarization may occur during a refractory period and start the repetitive AR-VS pattern.

Special algorithms can be programmed to restore 1:1 atrial tracking at rates slower than the

Table 2. Loss of cardiac resynchronization during DDD or DDDR pacing in the presence of preserved right and left ventricular pacing.

Intrinsic

1. Atrial undersensing from low amplitude atrial potentials.
2. T wave oversensing and other types of ventricular oversensing such as diaphragmatic potentials.
3. Long PR interval.
4. Circumstances that push the P wave into the PVARP such as a junctional or idioventricular rhythm.
5. New arrhythmia such as atrial fibrillation with a fast ventricular rate.
6. Short runs of unsustained, often relatively slow, ventricular tachycardia. Such arrhythmias are common and often asymptomatic.
7. First-generation devices with a common sensing channel: ventricular double counting and sensing of far-field atrial activity.

Extrinsic

1. Inappropriate programming of the AV delay or any function that prolongs the AV delay such as rate smoothing, AV search hysteresis, etc.
2. Low maximum tracking rate.
3. Slowing of the atrial rate upon exit from upper rate behavior.
4. Functional atrial undersensing below the programmed upper rate.
   A. Precipitated by an atrial premature beat or ventricular premature beat.
   B. Long PVARP including automatic PVARP extension after a premature ventricular complex and single beat PVARP extension related to algorithms for automatic termination of endless loop tachycardia.
5. Inappropriately slow programmed lower rate permitting junctional escape (cycle length < lower rate interval) in patients with periodic sinus arrest.
6. Intraatrial conduction delay where sensing of AS is delayed in the right atrial appendage. A short AS-VP interval may not be able to achieve biventricular pacing.

AV — atrioventricular, PVARP — postventricular atrial refractory period, AS — atrial sensed event, VP — ventricular paced event

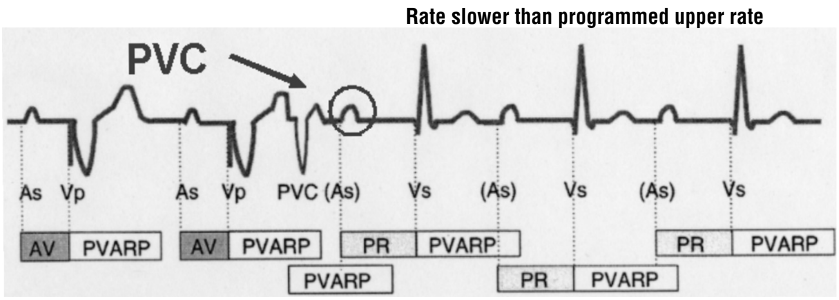

Figure 5. Diagrammatic representation of loss of ventricular synchronization induced by a premature ventricular complex (PVC). The sinus P wave following the PVC falls in the PVARP initiated by the PVC and is shown as "(As)" by the marker channel. This P wave is not tracked but it conducts to the ventricle giving rise to a QRS complex that is sensed by the pacemaker. The timing cycles are altered so that the sinus P waves now fall within the PVARP initiated by sensing the spontaneous QRS complex. Note that desynchronization or locking of the P waves within the PVARP occurs at a heart rate slower than the programmed upper rate. As — atrial sensed event, (As) — atrial sensed event within the pacemaker atrial refractory period, Vs — ventricular sensed event, AV — atrioventricular delay, PVARP — postventricular atrial refractory period, PR — PR interval (Courtesy of Guidant).

programmed upper rate (Figs. 8, 9). These algorithms are activated when the device detects AR in the PVARP. The algorithm temporarily shortens the PVARP and therefore the intrinsic TARP to permit sensing of the P wave beyond the PVARP so as to restore 1:1 atrial tracking. This algorithm may be useful in patients with sinus tachycardia and first-degree AV block in whom prolonged locking of the P waves inside the PVARP is an important problem. Such patients are sometimes best treated with ablation of the AV junction.

"Locking" of the P wave can often be prevented (barring reprogramming the device to eliminate the initiating mechanism e.g., T wave oversensing) with a shorter PVARP and slowing the sinus rate

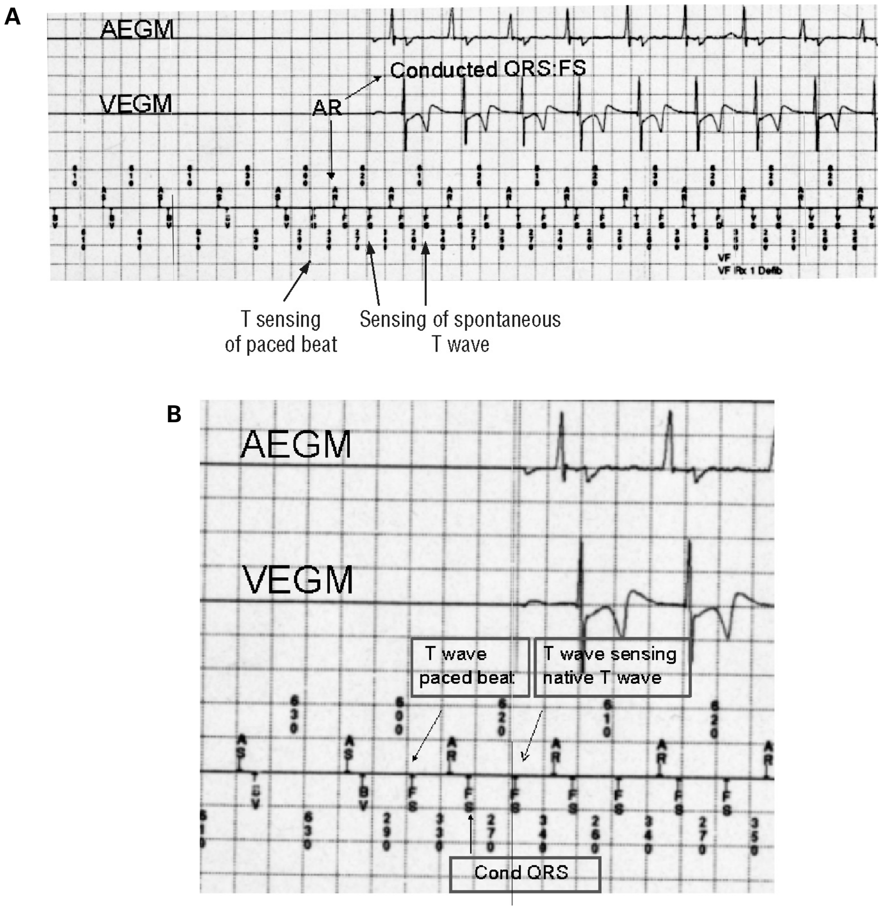

Figure 6. **A.** Stored electrograms showing ventricular desynchronization induced by T wave oversensing of a biventricular paced beat in a patient with a Medtronic InSync II Marquis biventricular ICD. **B.** A magnified portion at the bottom shows initiation of desynchronization in greater detail. Note that the sinus rate is relatively fast (P-P interval = 610–630 ms below the upper rate). The sequence starts with T wave oversensing of a paced beat (first arrow on the left) which then initiates ventricular desynchronization causing locking of the P wave in the PVARP (AR) which permits the emergence of the conducted spontaneous QRS complex. T wave oversensing also follows the spontaneous QRS complex. The device interpreted continual detection of both spontaneous QRS and T wave as ventricular fibrillation and subsequently delivered an inappropriate shock. T wave sensing of paced and spontaneous beats was subsequently reproduced at the time of follow-up. PVARP — postventricular atrial refractory period, AS — atrial sensed event, AR — atrial event detected in the atrial refractory period, BV — biventricular pacing event, AEGM — atrial electrogram, VEGM — ventricular electrogram, FS — ventricular fibrillation sense (Reproduced with kind permission from: Barold SS, Herweg B, Curtis AB. Loss of resynchronization by biventricular pacemakers: Mechanisms, diagnosis and therapy. Proceedings Venice Arrhythmia 2005 Meeting. Raviele A (ed.) Cardiac Arrhythmia 2005. Raviele A (ed.), Springer Italia 2006: 531–545).

with drugs. Refractory cases (usually associated with marked first-degree AV block) can be treated by AV junctional ablation.

Automatic unlocking of P waves from the PVARP. Automatic identification of an AR-VS pattern of cardiac activity to restore atrial tracking

Special algorithms (which must be programmed) based on beat-to-beat PVARP shortening upon sensing a P wave in the PVARP are now available (Figs. 8, 9). These algorithms do not function when the atrial rate is faster than the programmed upper rate or during automatic mode switching. This function promotes 1:1 atrial tracking whenever the “effective or prevailing TARP” [(AR-VS) + PVARP] prevents atrial tracking at rates below the programmed upper rate [2, 4–6]. A device can detect AR-VS, AR-VS… sequences suggestive of ventricular desynchronization whereupon temporary PVARP abbreviation permits the device to sense a sinus P wave beyond the PVARP and restore atrial tracking and ventricular resynchronization (Figs. 7–9). In other words, the algorithm shortens

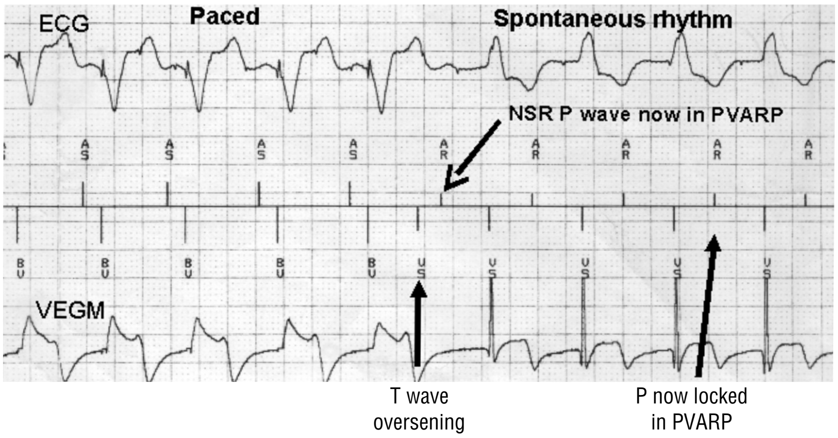

Figure 7. Ventricular desynchronization induced by T wave oversensing (VS, arrow) in a patient with marked first-degree AV block, left bundle branch block and a Medtronic InSync II Marquis biventricular ICD. Lead II ECG is on top, markers in the middle and the ventricular electrogram from the right ventricular apex at the bottom. The sinus rhythm remains undisturbed. VS (related to T wave oversensing) initiates a new PVARP into which the succeeding P wave is detected as AR (in the atrial refractory period) but not tracked. AR conducts to the ventricle as VS with a long PR interval thereby perpetuating the desynchronization process with the sinus P waves (locked in the PVARP) continually conducting to the ventricle. PVARP — postventricular atrial refractory period, AS — atrial sensed event, AR — atrial sensed event in the pacemaker atrial refractory period, VS — ventricular sensed event, VEGM — ventricular electrogram, NSR — normal sinus rhythm (Reproduced with kind permission of Springer Science and Business Media [2]).

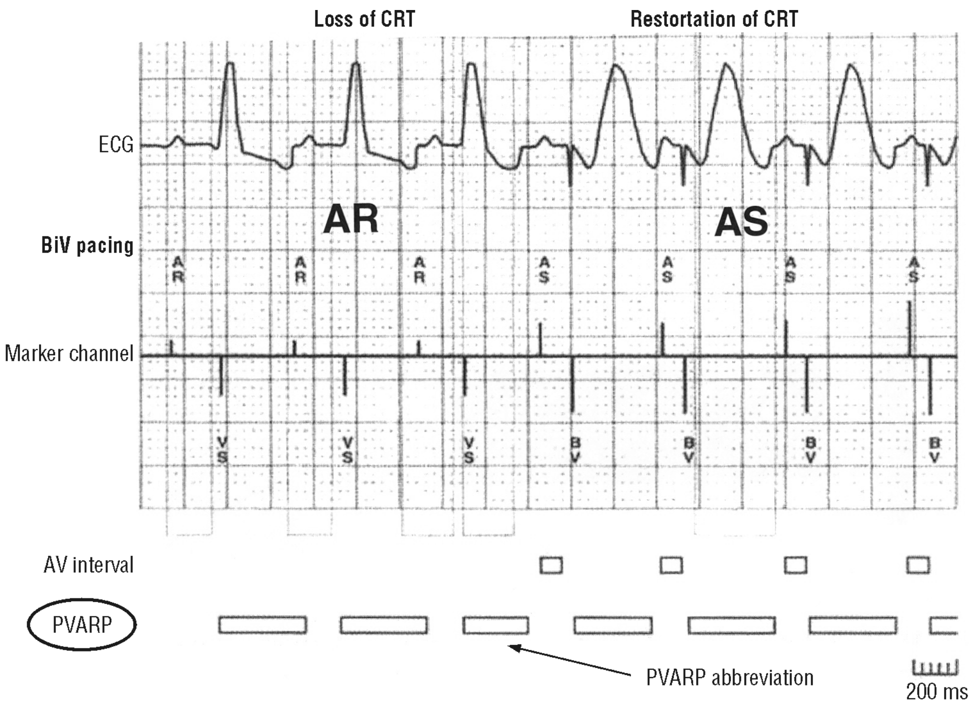

Figure 8. Atrial tracking recovery algorithm (Medtronic) during biventricular pacing. Abbreviation of the PVARP promotes recovery of atrial tracking, and resynchronization. The algorithm recognizes VS-AR sequences only when the VS-VS interval is longer than the programmed upper rate interval. Atrial events must occur during the PVARP. After eight AR-VS cycles, the device intervenes by shortening the PVARP. The sinus P wave now resides outside the PVARP and is sensed and tracked as AS. This restores resynchronization with AS-VP sequences. If the attempt fails, the process continues until AS-VP intervals are restored at their programmed value. PVARP — postventricular atrial refractory period, AS — atrial sensed event, AR — atrial sensed event in the pacemaker atrial refractory period, VS — ventricular sensed event, CRT — cardiac resynchronization therapy. Guidant devices have a similae algorithm called atrial tracking preference (Courtesy of Medtronic Inc).

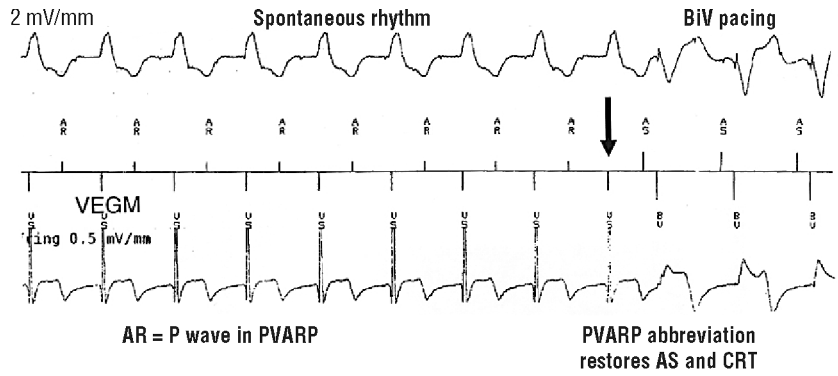

Figure 9. Same patient and format as in Figure 7. On the left the pattern of ventricular desynchronization (AR-VS sequences) is identical to that in Figure 7. The ICD restores ventricular resynchronization with an algorithm that detects a specific number of AR-VS sequences (interpreted by the device as loss of resynchronization) and then temporarily abbreviates the PVARP (arrow). The shorter PVARP permits P wave tracking and restores resynchronization (AS-VP sequences at the programmed value) on the right of the recording. AS — atrial sensed event, AR — atrial sensed event in the pacemaker atrial refractory period, VS — ventricular sensed event, VP — ventricular paced event, PVARP — postventricular atrial refractory period, VEGM — ventricular electrogram (Reproduced with kind permission of Springer Science and Business Media [2]).

the TARP. A P wave falling in the postventricular atrial blanking period (for pacing) cannot activate the special algorithm.

Subsequent AS-VP intervals are shortened even more as the intervention proceeds in an attempt to terminate the AR-VS pattern. The shortening of the sensed AV (SAV) interval (initiated by atrial sensing) however, is a function of the pacemaker upper rate behavior. Since the SAV interval is normally programmed to an interval that is shorter than the intrinsic conduction time, a ventricular pacing stimulus is provided at the end of the AS-VP interval, thereby effectively restoring resynchronization.

Paced QRS complex and status of ventricular resynchronization

The paced QRS during biventricular pacing (utilizing the coronary venous system) is often narrower than the pattern registered during monochamber ventricular pacing [1]. Barring ventricular fusion beats (with the conducted QRS complex), a narrower QRS implies depolarization by both RV and LV channels.

RV lead at the apex, and LV lead in the coronary venous system

The frontal plane QRS axis is usually in the right superior quadrant. The frontal plane axis may occasionally reside in the left rather than the right superior quadrant. The QRS is often positive in lead V1 during biventricular pacing.

Significance of a negative QRS complex in lead V1 during biventricular pacing

A negative QRS complex in lead V1 during uncomplicated biventricular pacing probably reflects altered activation of an heterogeneous biventricular substrate (ischemia, scar, His-Purkinje participation in view of the varying patterns of LV activation in spontaneous LBBB etc. and may not necessarily indicate a poor (electrical or mechanical) contribution from LV stimulation. However, such a pattern in lead V1 requires exclusion of incorrect placement of lead V1 (too high on the chest), ventricular fusion (with the spontaneous QRS complex), lack of LV capture, LV lead displacement, presence of pacing via the middle cardiac vein or great cardiac vein or even unintended placement of 2 leads in the RV [1]. In this situation, it is also imperative to rule out marked latency (exit block or delay from the LV stimulation site), an important but poorly studied phenomenon that may generate the pattern of RV depolarization during biventricular pacing and can be compensated by V-V timing that alters the timing between LV and RV pacing [11].

RV lead in the outflow tract, and LV lead in the coronary venous system

We have found that during biventricular pacing with the RV lead in the outflow tract the paced QRS in lead V1 is often negative and the frontal plane paced QRS axis is often directed to the right inferior quadrant (right axis deviation) [1]. Further studies are required to confirm these preliminary findings and determine the significance of these ECG patterns of biventricular pacing according to the RV pacing site.

Ventricular fusion beats with native conduction

In patients with sinus rhythm and a relatively short PR interval, ventricular fusion with competing native conduction during biventricular pacing may cause misinterpretation of the ECG, a common pitfall in device follow-up [1]. Elimination of ventricular fusion may produce substantial clinical improvement in some patients. Marked QRS shortening mandates exclusion of ventricular fusion with the spontaneous QRS complex, especially in the setting of a relatively short PR interval. The presence of ventricular fusion should be ruled out by observing the paced QRS morphology during progressive shortening of the AS-VP interval in the VDD mode or the AP-VP interval in the DDD mode if necessary. The AS-VP interval should be then programmed (with rate-adaptive function) to ensure pure biventricular pacing under circumstances that might shorten the PR interval such as increased circulating catecholamines. It is conceivable that in some circumstances, fusion with the spontaneous QRS complex might be beneficial. In the absence of firm data or guidelines this option should perhaps be explored on a trial basis in selected patients who are not doing well.

Atrial fibrillation

Some devices have programmable algorithms that increase the percentage of biventricular pacing during atrial fibrillation so as to promote some degree of rate regularization (without an overall increase in the ventricular rate) by dynamic matching with the patient's own ventricular responses (up to the programmed maximum tracking rate) (Fig. 10). Activation of this algorithm does not result in control of the ventricular rate, and should not be a substitute for ablation of the AV junction in patients with drug-refractory rapid ventricular rates.

Cardiac resynchronization by virtue of reverse remodeling may promote the return of sinus rhythm in some patients, but no firm data are yet available. Furthermore, patients with permanent atrial fibrillation may have a greater likelihood of staying in sinus rhythm after cardioversion when it is performed after several months of device therapy and aggressive antiarrhythmic therapy [12–14]. This raises the question as to whether an atrial lead should be implanted during the initial procedure (with or without intraoperative cardioversion) in patients with permanent atrial fibrillation in whom cardioversion might be contemplated in the future.

Intra- and interatrial conduction delay

Some patients have intraatrial conduction delay so that the atrial channel senses the atrial

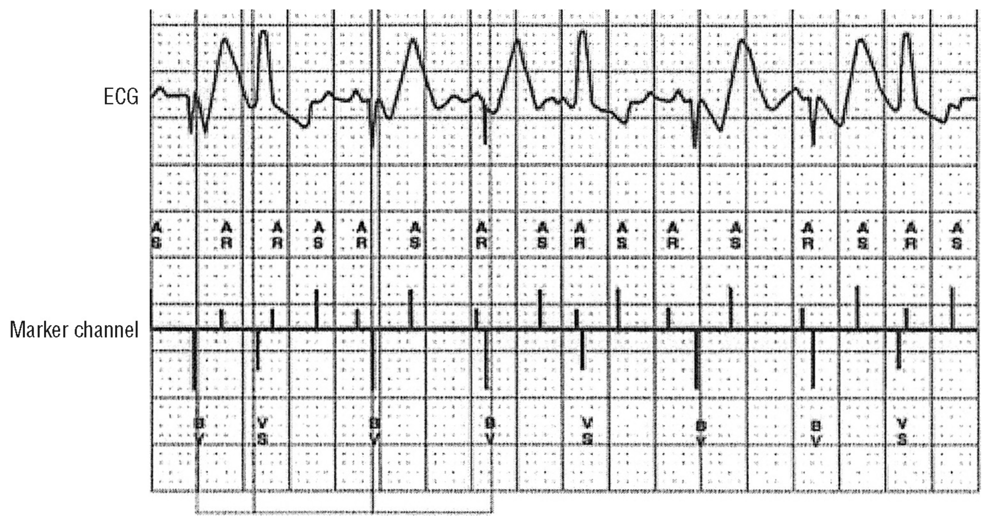

Figure 10. Diagrammatic representation of the Medtronic conducted atrial fibrillation (AF) Response algorithm. The device can be programmed to increase the pacing rate in concert with the patient's ventricular response. By dynamically matching the patient's response to AF, the device can increase the percentage of ventricular pacing with little or no increase in the daily average heart rate (Courtesy of Medtronic Inc).

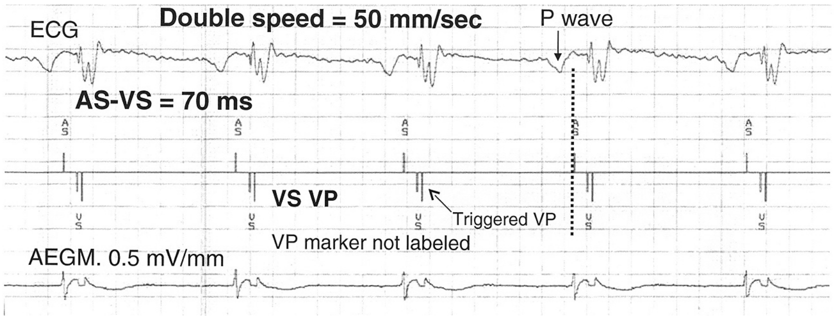

Figure 11. Ventricular resynchronization upon RV sensing by the ventricular triggered mode of a Medtronic biventricular ICD. The patient has intraatrial conduction delay so that the atrial electrogram sensed in the atrial appendage occurs late during the isoelectric portion of PR interval (dotted vertical line). The AS-VS interval during AV conduction measures only 50–60 ms. The patient did not tolerate an AS-VP interval of 40 ms to produce biventricular pacing which in all likelihood occurred with some degree of fusion with the spontaneous conducted QRS complex. This situation calls for one of 2 options. 1. Ablation of the AV junction; 2. Using the triggered mode upon sensing. A trial of the triggered mode produced marked clinical improvement. Consequently the pacemaker was programmed to the ventricular triggered mode for long-term pacing. AS is followed by VS (smaller downward deflection) which triggers VP (larger downward deflection). AEGM — atrial electrogram, AS — atrial sensed event, VS — ventricular sensed event, VP — biventricular paced event, RV — right ventricle, AV — atrioventricular (Reproduced with permission from [1]).

electrogram from the atrial appendage late and during the isoelectric portion of the PR interval [15]. The AS-VS interval (as seen by the pacemaker) during spontaneous AV conduction becomes quite short and can measure only 50–60 ms (Fig. 11). Such patients may not tolerate an AS-VP interval of 40 ms or less to produce biventricular pacing which in all likelihood might be associated with some degree of fusion with the spontaneous conducted the QRS complex. This situation calls for one of two options: 1. Using the ventricular triggered mode upon sensing the QRS complex after the sensed P wave. A trial of the triggered mode might produce the desired clinical improvement; 2. Ablation of the AV junction with subsequent optimization of the AV delay.

Ventricular triggered mode

The ventricular triggered mode in some resynchronization devices automatically attempts to provide resynchronization in the presence of ventricular sensing. A ventricular sensed event initiates an immediate emission of a ventricular or usually a biventricular output (according to the programmed settings) in conformity with the programmed upper rate interval. For example, Medtronic devices offer this function in the VVIR mode, but in dual chamber devices triggering occurs upon sensing only within the programmed AV delay. The ventricular output will be ineffectual in the chamber where sensing was initiated because the myocardium is physiologically refractory. The stimulus to the other ventricle thus attempts to provide a measure of resynchronization. Ventricular triggering may be helpful in some patients but its true benefit is difficult to assess as the ventricles may be activated in an order that may not be hemodynamically favorable.

Conclusion

The physician must ensure that biventricular pacing takes place 100% of the time. The percentage of biventricular pacing and ventricular sensing must be carefully checked in the stored memorized data retrieved from the device. Devices must be programmed carefully to prevent desynchronization (Table 3). Troubleshooting loss of resynchronization may be difficult and requires a thorough knowledge of biventricular pacemaker function, timing cycles, and complex algorithms. Partial (as in fusion beats), intermittent or complete desynchronization should always be ruled out in patients presenting with decompensated congestive heart failure, bearing in mind that the optimal or effective AV delay and other indices may require change with time [17, 18].

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Table 3. Optimal programming of biventricular pacemakers.

AV delay

1. A long AV delay should not be used.
2. Optimize the AS-VP delay and avoid ventricular fusion with the spontaneous conducted QRS complex.
3. Program rate-adaptive (dynamic) AV delay off during temporary pacing for testing (with VDD mode slower than sinus rate to sense atrial activity).
4. Programming rate-adaptive AV delay for long-term pacing is controversial [16].

Atrial sensing and PVARP

1. Short PVARP (aim for 250 ms). May have to use algorithms for the automatic termination of endless loop tachycardia.
2. Program off the post-VPC PVARP extension and the pacemaker-mediated tachycardia termination algorithm based on one cycle of PVARP extension.
3. Automatic mode switching off in devices using a relatively long PVARP mandated by the mode switching algorithm.

Upper rate

Relatively fast upper rate so the patient does not have "break-through" ventricular sensing within their exercise zone. Initial upper rate of 140/min is often appropriate in the absence of myocardial ischemia during pacing at this rate.

AV conduction

1. Use drugs that impair the AV conduction to avoid ventricular fusion or double counting in devices with a common sensing channel.
2. Consider ablation of AV junction in patients with a long PR interval or intra- or interatrial conduction delay difficult to manage as well as refractory double counting (common sensing channel).

AV — atrioventricular, AS — atrial sensed event, VP — ventricular paced event, PVARP — postventricular atrial refractory period, VPC — ventricular premature complex

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