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Review article

# Advanced pacing algorithms resembling device malfunction: A comprehensive review☆

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ABSTRACT

Pacemakers have evolved from old-school demand pacing to providing tailored therapies. Nowadays, sophisticated algorithms adapt to changing pacing thresholds and provide an artificial chronotropic response while reducing ventricular pacing and preventing dangerous external interferences, among other functions. This way, pacing has become more physiological, maximizing battery duration and increasing patient safety and quality of life. However, this rising in complexity has made their electrocardiogram harder to interpret. In many cases, these functions may create unusual pacing patterns that could sometimes be mistaken for a device malfunction, prompting unnecessary use of medical resources and patient anxiety that could be avoided if such patterns were recognized. This review presents and explains those different advanced functions and algorithms, classified by their apparent malfunction, as a reference for the general cardiologist.

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**Algoritmos avanzados de estimulación que simulan disfunciones de dispositivos: una revisión exhaustiva**

*Palabras clave:*
Marcapasos
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RESUMEN

Los marcapasos han evolucionado de la antigua estimulación a demanda a un tratamiento individualizado. Hoy en día, mediante complejos algoritmos son capaces de adaptarse a cambios en el umbral de estimulación, proporcionar una respuesta cronotrópica artificial, reducir la estimulación ventricular y evitar el peligro de interferencias externas, entre otras funciones. Gracias a ello, la estimulación es más fisiológica, alargando la duración de la batería y aumentando la seguridad y calidad de vida del paciente. Sin embargo, esta complejidad creciente ha hecho que el electrocardiograma sea más difícil de interpretar. En muchos

☆ *Abbreviations:* AS, atrial sensing; AP, atrial pacing; AVI, atrioventricular interval; ELT, endless loop tachycardia (pacemaker-mediated); VS, ventricular sensing; VP, ventricular pacing.

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casos estas funciones crean patrones de estimulación inusuales que se pueden confundir con disfunciones, provocando un uso innecesario de recursos sanitarios y preocupación por parte del paciente que podrían evitarse si se reconocieran tales patrones. Esta revisión presenta y explica esos algoritmos y funciones, agrupados según la disfunción aparente, para la consulta por el cardiólogo general.

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## 1. Introduction

Every year, some 500 000 patients receive a pacemaker in the European Union.[1] During the last decades, pacemakers have evolved to be sophisticated devices, far from demand VVI pacing as they were conceived in the sixties. With the intention of being more physiological and provide a patient-tailored therapy, they have incorporated an array of advanced features. Some of these focus on patient safety, such as ventricular safety pacing to prevent cross-talk inhibition, or on pacing threshold measurement to ensure appropriate capture. Others have an impact on patient quality-of-life, such as sensor-driven rate responsiveness to increasing functional capacity, or ventricular pacing (VP) reduction to reduce adverse ventricular remodeling. To give it another twist, other algorithms like transthoracic impedance measurement use sub-threshold currents that some electrocardiogram (ECG) recorders might depict as false pacing artifacts. All in all, these algorithms have in common an apparently abnormal behavior when registered in an ECG. When a pacemaker is expected to work just as single-chamber demand or dual-chamber sequential pacing, the observation of abnormally short (fast) or long (slow) intervals or an apparent failure to sense or to capture, will raise concerns about its normal operation.

In those scenarios, the patient can be given an appointment for an in-person device check-up, but even then, the allegedly abnormal behavior may not be replicated. Only a thorough knowledge of the rules controlling such algorithms may reassure the clinician on discriminating real malfunctions from normal, though complicated, functioning pacemakers. On the other hand, it is virtually impossible to know all the parameters and settings involved in every algorithm for each pacemaker and manufacturer.

Considering that the clinician never knows which particular algorithm is operating when facing an ECG, and that only sees what appears to be a malfunction, a structured approach is paramount. This review is structured according to the malfunction purportedly observed. Then, the different options to such behaviors are explained, including a comprehensive list of the logic ruling the different algorithms from each manufacturer, European and American. Throughout the text, manufacturers are referred to by their current or best known registered trademark: in this regard, it should be noted that ELA changed to Sorin, then to Livanova and lately became MicroPort, Guidant became Boston Scientific, Pacesetter became St. Jude and then Abbott, and Vitatron became Medtronic. With these tools, the clinician will be able to ascertain whether the pacemaker works according to the logic of the algorithm, strange as it may be, or whether it violates any of them, which will indicate a device malfunction.

## 2. Short atrioventricular interval

Dual-chamber pacemakers are expected to pace the ventricles some 110–220 ms after an atrium is sensed or paced. When an abnormally short atrioventricular interval (AVI) is observed, the relationship between the sensed/paced atrium and the paced ventricle, as well as the AVI value itself, will provide the clue to the underlying function.

### 2.1. *Ventricular safety pacing*

Atrial pacing pulses might be sensed in the V channel, a phenomenon also known as "crosstalk". This inappropriate ventricular sensing (VS) will result in ventricular inhibition: should the patient be pacemaker dependent, this ventricular inhibition will cause asystole. Thus, VS in a narrow window following atrial pacing (AP) will trigger a safety pacing to warrant VP and prevent pauses or asystole. However, a ventricular premature beat might also happen just simultaneous with an AP. In this case, if ventricular safety pacing was delivered after a normal AVI, i.e. 200 ms, it might pace during a vulnerable period and trigger a ventricular arrhythmia. Therefore, ventricular safety pacing occurs after a short, preset interval (110 ms in Biotronik[2] and Medtronic,[3] 120 ms or programmed AVI if shorter in Abbott,[4] 95 ms in Sorin[5]) so that the ventricles are paced and captured, in case of crosstalk, or it falls in a refractory period, in case of a ventricular premature beat (Fig. 1).

### 2.2. *Capture control and threshold search*

This feature is intended to increase patient safety by guaranteeing ventricular capture[6] as well as to reduce battery drain by adjusting pulse amplitude to the lowest value required to maintain capture.[7] Some manufacturers (Abbott ACap and RVCap Confirm, Biotronik, Boston Scientific) provide beat-to-beat capture confirmation by assessing the evoked response of the action potential after myocardial capture.[8] If capture does not occur in a particular beat, a backup safety pulse of greater amplitude and/or duration is provided. Other devices only perform regular searches of pacing thresholds (Abbott AutoCapture,[4] Medtronic, Sorin). When evaluating the ventricular threshold, intrinsic conduction and fusion must be ruled out, so V will be paced after a short AVI. The test VP is followed by a backup VP with higher output to warrant capture

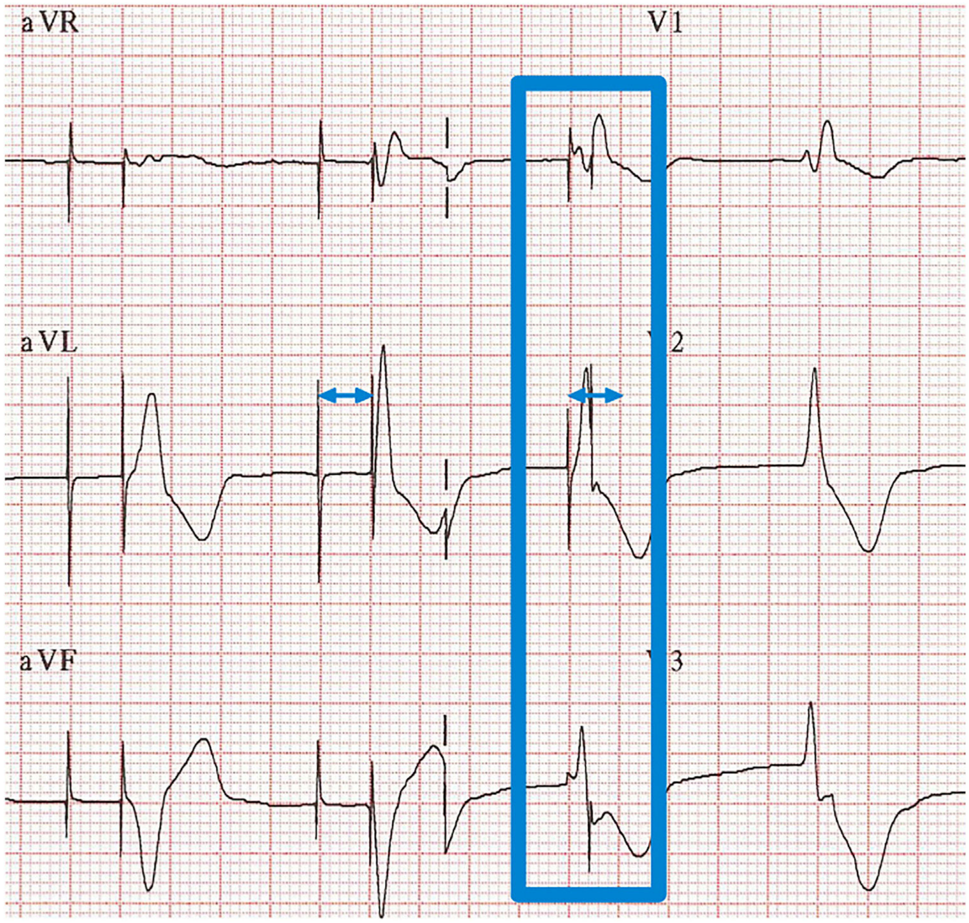


**Fig. 1 – Ventricular safety pacing. Dual-chamber pacemaker (in a patient with atrial fibrillation and undersensing of waves). The first two beats show sequential atrioventricular pacing at the programmed atrioventricular interval (AVI) (blue double-headed arrow), with the second being a fusion (narrower than purely paced QRS). The third beat shows atrial pacing simultaneous with a conducted beat sensed in the ventricular channel, thus triggering a ventricular safety pacing with sequential atrioventricular pacing at a much shorter AVI.**

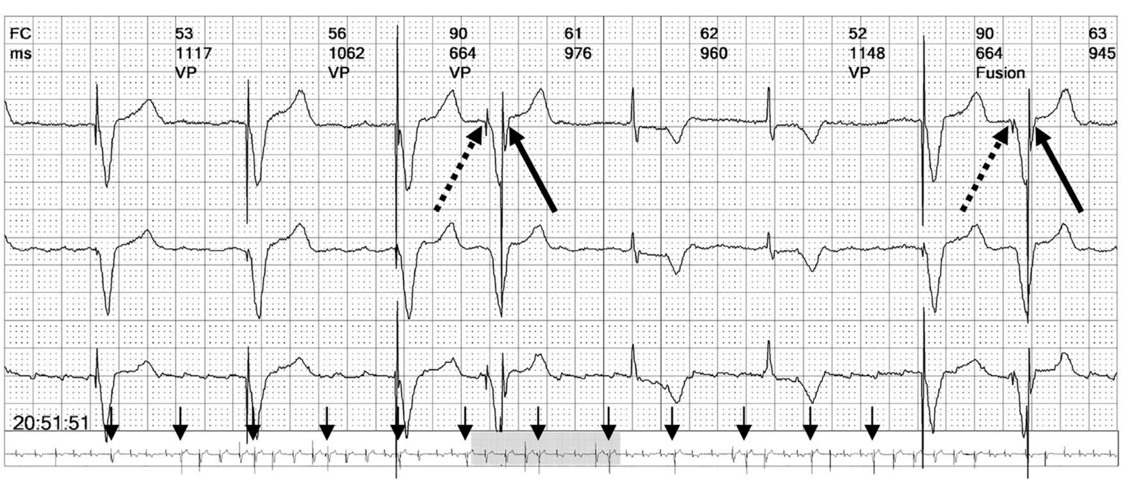


**Fig. 2 – Threshold search. This VVI Medtronic Sensia pacemaker is programmed at a lower rate limit of 55 bpm. Every four cycles (see lower rhythm strip), a test pace (dashed arrow) is followed at 110 ms by a backup pace (solid arrow).**

**Table 1 – Autothreshold measurement.**

| Manufacturer | Mode of operation | Measurement interval | Default setting |
|---|---|---|---|
| Abbott[4,9] | Capture is assessed in any case by ER. Bipolar lead required<br>• Atrium (ACap): atrium is paced faster (not above 120 bpm) with decreasing output amplitude until 3 LoC beats occur<br>• Ventricle:<br>○ Beat-to-beat confirmation (RVCap Confirm): backup VP at 63 ms when no ER is detected<br>○ Threshold search (AutoCapture): in DDD, sensed AVI is 25 ms and paced AVI is 50 ms. In VVI, VP is provided at decreasing amplitudes every beat until two consecutive LoC (with their backup pulses) are detected. However, ventricular rate will not be overridden for the test; hence, if there is spontaneous rhythm, no threshold search will be performed[10] | Every 8 h | Off |
| Biotronik[2,11] | • Atrium: Capture is assessed by sinus reset, pacing in DDI at 20% faster than current rate (up to 108 bpm), in decreasing amplitude steps. When 2 AS are detected in a 5-beat window, atrial LoC is declared. The measurement is confirmed by repeating the test, starting at the lowest confirmed amplitude and decreasing in smaller steps<br>• Ventricle (Ventricular Capture Control): Capture is assessed by ER<br>○ Beat-to-beat confirmation: backup VP at 130 ms when no ER is detected<br>○ Threshold search: In DDD, sensed AVI is 15 ms and paced AVI is 50 ms. In VVI, there will be pacing 20% faster than the current rate (up to 110 bpm). VP is provided at decreasing amplitudes every beat. In the case of LoC, a backup pulse is given. The test is repeated starting at the lowest confirmed amplitude and decreasing in smaller steps to confirm the measurement | Every 24 h (at 00:30) | On |
| Boston Scientific[12] | PaceSafe. Capture is assessed in any case by ER. Bipolar lead required<br>• Atrium: AP with test pulses at up to 20 bpm faster than average atrial rate (but no faster than 110 bpm, maximum tracking or sensor rate, whichever is lower). There are no backup atrial pulses. AVI 55–85 ms. No beat-to-beat assessment<br>• Ventricle:<br>○ Beat-to-beat confirmation: backup Vp at 70 ms when no ER is detected<br>○ Threshold search: in DDD, sensed AVI is 30 ms and paced AVI is 60 ms. In VVI, pacing will occur 10 bpm faster than current rate (up to 110 bpm or maximum programmed rate, whichever is lower). Pacing amplitude is decreased every 3 beats. After every test pacing pulse over 3.5 V, a backup pulse at 70 ms is provided | Every 21 h | On |
| Medtronic[13–15] | • Atrium (*Atrial Capture Management*)<br>○ If in sinus rhythm but rate <87 bpm, capture is assessed by atrial reset. 3 AS are followed by an earlier test AP, and this is followed by two "stabilization" AS. If the test AP does not capture, an atrium will be sensed shortly after that AP<br>○ If atria are paced but AV conduction is preserved, VS after a test AP will be considered a surrogate of atrial capture. 3 AP cycles at programmed output are followed by a test AP, and this is followed by a support AP (at 1 ms pulse width) after 70 ms<br>• Ventricle: Capture is assessed by ER. 3 VS/VP support cycles at programmed settings, followed by a test VP, and this is followed by a backup VP after 90 ms (series Amplia, Compia), 100 ms (series Ensura) or 110 ms (series Adapta, Versa, Sensia)<br>• CRT: Each lead is tested pacing separately<br>○ RV lead is tested as reported above<br>○ LV lead is tested similarly (3 support VP followed by one test VP) but without backup VP; RV sensing is used to assess LV capture | Every 24 h | On |
| Sorin | • Atrium:<br>○ If sinus rhythm stable and <80 bpm, capture is assessed by sinus reset. Every fourth beat is advanced 200 ms and paced at increasing amplitudes until no AS happens after the test AP, and the measurement is confirmed by a repeat 4-beat test cycle at the successful amplitude<br>○ If no sinus rhythm, atrial rate unstable or measurement unreliable, atrial capture is assessed using conducted VS as a surrogate<br>• Ventricle: Capture is assessed by ER. In DDD, AVI is 110 ms. In VVI, heart rate will be overdriven up to 95 bpm. VP is provided at decreasing amplitudes every beat. In the case of LoC, a backup pulse at 64 ms is delivered | Atrium: daily<br>Ventricle: every 6 h | Off |

AP, paced atrial beat; AS, sensed atrial beat; AVI, atrioventricular interval; bpm, beats per minute; CRT, cardiac resynchronization therapy; ER, evoked response; LoC, loss of capture; LV, left ventricular; RV, right ventricular; VS, sensed ventricular beat; VP, paced ventricular beat.
Manufacturers' names are listed in alphabetical order. Figures refer to nominal (standard) settings. Data for Sorin obtained from technical support and on-screen device interrogator help.

in case the testing stimulus fell below the capture threshold (Fig. 2). In this case, regularity is key: threshold measurements are performed by repeating runs of baseline cycles alternating with test cycles (Table 1).

### 2.3. *Negative hysteresis*

This feature is used mainly by Abbott and Biotronik in cardiac resynchronization therapy since it targets to maximize VP. In Abbott devices, the AVI after a VS is shortened for 31 cycles, and if another VS occurs meanwhile, that shortening will be kept for 255 cycles up to 120 ms shorter than programmed AVI.[4] Biotronik shortens the programmed AVI up to 50 ms.[2]

### 2.4. *Dynamic atrioventricular interval*

Pacemakers can adapt AVI in a physiological way, shortening it at faster heart rates. Usually, both rest (longer) and exercise (shorter) AVI values can be preset and changes between them are made in a linear fashion by the pacemaker; other devices,

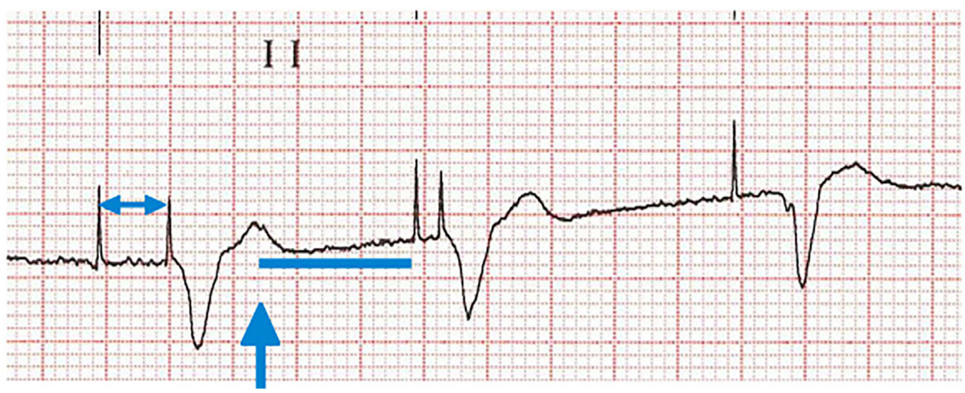


**Fig. 3 – Sorin WARAD. This algorithm prevents and recognizes atrial arrhythmia. After an atrial premature contraction (arrow), the atrium is paced after 500 ms regardless of the programmed lower rate limit, and the ventricle is paced after 80 ms (shortest exercise atrioventricular interval).**

**Table 2 – Atrioventricular hysteresis algorithms.**

| Manufacturer | Trade name | Rules | Evaluation frequency (search interval) | Default setting |
|---|---|---|---|---|
| Abbott | VIP | • Extends AVI in 100 ms for 1 cycle. If there is VS, the extended AVI is kept in effect<br>• Operation suspended when intrinsic A or sensor rate is 110 or faster | Every minute | Off |
| Biotronik | IRSplus | • Extends AVI to 400 ms for 10 cycles. If there is VS, the extended AVI is kept in effect | • After a single VS<br>• Every 180 VP | Off |
| Boston Scientific | AV Search+ | • Extends AVI to 300 ms for 8 cycles. If there is VS, the extended AVI is kept in effect<br>• Reverts to programmed AVI when ≥2/10 V are paced | Every 32 cycles | Off |
| Medtronic | SearchAV+ | • Extends AVI in 62 ms for 16 cycles. If there are ≥8/16 VP, AVI is extended other 62 ms up to a maximum 170 ms more than programmed AVI<br>• If ≥8/16 VS shorter than extended AVI minus 55 ms, AVI is shortened in 8 ms steps<br>• Permanently suspended after 10 consecutive failed 16-h search attempts | At intervals progressive longer if no intrinsic conduction is found: 15 min, 30 min, 1, 2, 4, 8 and 16 h intervals | Off |
| Sorin | DPlus | • Extends AVI to 350 ms<br>• Reverts to programmed AVI after a single VP | • After a single VS.<br>• Every 100 VP, AVI lengthens for 5 cycles<br>• Change from AP to AS, AVI lengthens for 5 cycles | Off |

AVI, atrioventricular interval; IRS, intrinsic rhythm support; VIP, ventricular intrinsic preference; VS, sensed ventricular beat; VP, paced ventricular beat.
Manufacturers' names are listed in alphabetical order. Figures refer to nominal (standard) settings. Data for Sorin obtained from teaching documents.

such as Biotronik, allow for customization of the profile of atrioventricular (AV) adaptation. Thus, an AVI as short as 65 ms at high atrial rates can be expected.[12]

### 2.5. Non-competitive atrial pacing

Medtronic pacemakers try to avoid AP shortly after an atrial premature contraction where it might trigger atrial arrhythmia.[13] Hence, an AS (atrial sensing) shortly after a ventricle (during the post-ventricular atrial refractory period) will trigger a 300 ms interval that might delay the next AP. To balance the cardiac cycle for this delay in AP, the AV interval might be shortened up to a minimum 30 ms. Sorin uses the WARAD (Window of Atrial Rate Acceleration Detection) algorithm, whose functioning is more complicated since it depends on the basal rate, timing of atrial premature contraction and existence of previous atrial premature contractions.[16] To summarize, WARAD will pace the atria 500 ms after an atrial premature contraction, and the ventricle 80 ms thereafter (Fig. 3).

## 3. Long atrioventricular interval

A long AVI is usually due to algorithms facilitating intrinsic conduction. They run in a periodic basis, performing rounds to check AV conduction during which abnormal AV intervals can be found. In other cases, they set an apparently abnormal AVI as an operating value.

### 3.1. Atrioventricular hysteresis

This is the simplest form of promoting intrinsic conduction. AV hysteresis algorithms simply lengthen AVI on a periodic basis to allow for existent but slow AV conduction to occur. If there is VS within the extended interval, that new AVI will be kept: otherwise, pacing returns to the preset AVI until the next checking round. In some cases, if no intrinsic conduction is observed after several verifications, the algorithm is disabled until the device is interrogated. These algorithms have shown to reduce VP, while other clinical benefits remain unproven.[17]

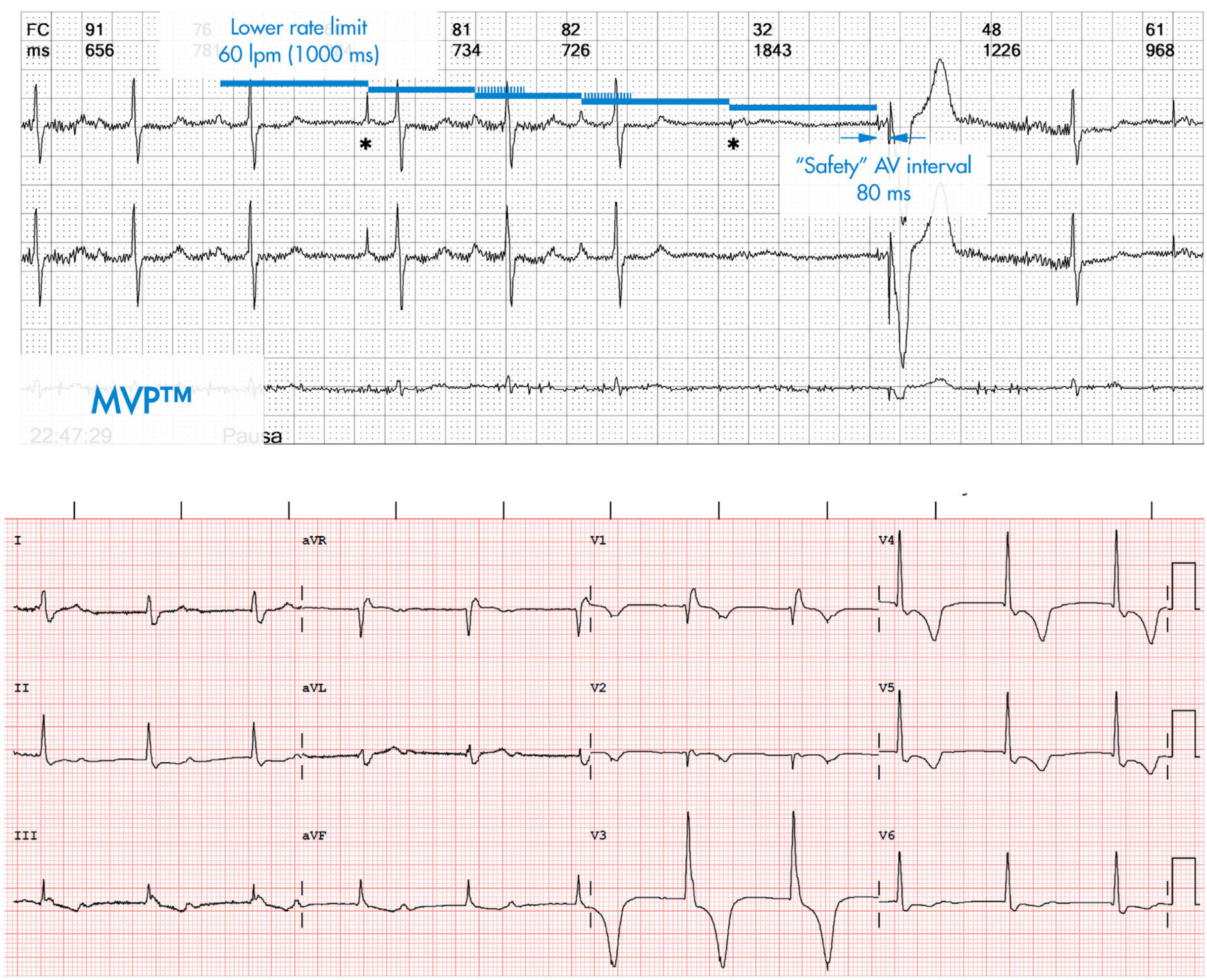


**Fig. 4 – Medtronic Managed Ventricular Pacing. Upper: Holter recording showing sinus rhythm or atrial pacing (asterisk) at a lower rate limit. When an A–A elapses with no conducted QRS, a ventricular pace is delivered at a lower rate limit plus 80 ms. Modified with permission from Higueras et al.[18] Lower: Pacemaker operating in AAI mode with long (~600 ms) intrinsic AV interval. New Medtronic pacemakers have corrected such behavior.**

Their main feature, that differentiates them from other V pacing reduction algorithms, is that in AV hysteresis every atrium is followed by a ventricle, either paced or sensed. A comprehensive list of their different registered names and rules of operation is provided in Table 2.

### 3.2. *Ventricular pacing reduction algorithms*

This could probably be the most common pseudo-malfunction encountered in Holter-ECG, since intrinsic AV conduction assessment occurs several times during a 24-h recording. In some cases, they may cause short pauses or atrial cycles without their corresponding ventricle (Fig. 4, Fig. 5, Fig. 6). These algorithms have proved useful to reduce the percentage of VP in patients with relatively preserved AV conduction (i.e. sinus node dysfunction, Wenckebach AV block during exercise or paroxysmal AV block).[17] Their different implementations have been proven more effective than AV hysteresis in reducing VP.[19,20] They follow different rules depending on the manufacturer (Table 3). As a whole, they operate as atrial-managed modes with VP backup: hence, they are sometimes referred to as AAI ↔ DDD. When some conditions are met, such as a number of A without V, maximal pause duration or AVI, they switch to a DDD pacing mode. Boston Scientific's Rhythmiq is a particular case thereof.[12] It is conceived as AAI(R) operating at a lower rate or sensor rate, plus a backup VVI running behind at atrial rate minus 15 beats per minute (bpm), but neither slower than 30 nor faster than 60 bpm (Fig. 5).

## 4. Fast pacing rates

Many physicians think of a pacemaker as a device that ensures a minimum ventricular rate, usually 60 bpm. That is why, when faced to a device pacing at faster rates, even over 100 bpm, they are concerned about its normal functioning. However, there are several situations in which it is desirable for the pacemaker to pace faster than that lower rate limit.

### 4.1. *Sensor-driven rate*

Pacemakers can become more physiological by increasing their lower rate according to metabolic demands, which is particularly useful in patients with chronotropic incompetence or pacemaker dependency. For that purpose, all current

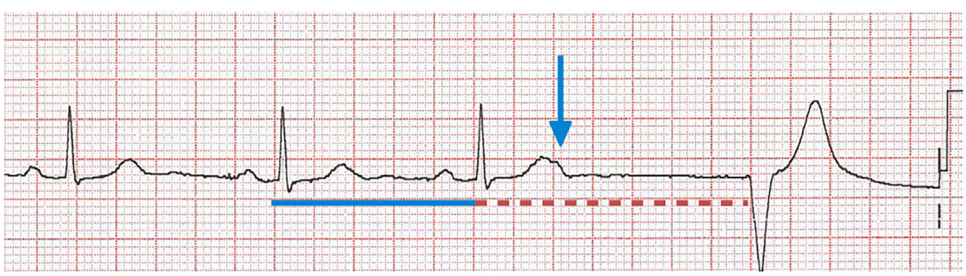

**Fig. 5 – Boston Rythmiq. Patient with a dual-chamber pacemaker programmed at 60 bpm. See atrial pacing at lower rate limit with intrinsic atrioventricular conduction at 60 bpm (blue line). There is an atrial premature complex (arrow), but it is not followed either by sequential ventricular pacing (VP) after an atrioventricular delay or by VP at lower rate limit. Contrarily, VP occurs at 45 bpm (1400 ms, dashed red line), that is 15 bpm less than lower rate limit. Rythmiq functions as an AAI-managed mode with VVI running in the background at 15 bpm slower than lower rate limit.**

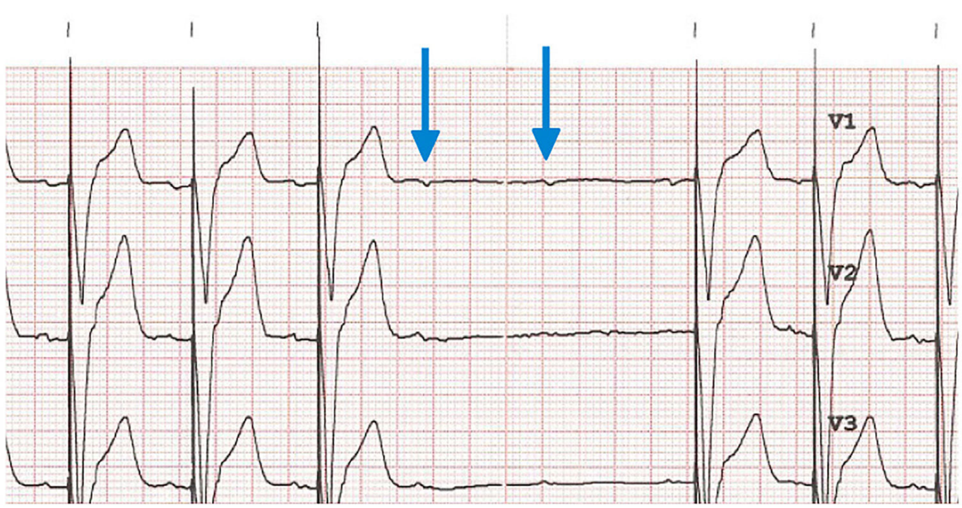


**Fig. 6 – Sorin SafeR. Patient with complete atrioventricular block. The device is operating in DDD mode tracking sinus rhythm when it performs a conduction test, allowing two consecutive P waves (arrows) not to be conducted to the ventricles, then it resumes DDD operation.**

**Table 3 – Ventricular pacing reduction algorithms.**

| Manufacturer | Trade name | Switch to DDD | Switch to atrial-based | Default setting |
|---|---|---|---|---|
| Abbott | *No such algorithm; only AV hysteresis* | | | |
| Biotronik | VP suppression | • No VS for 2 s (beware that, as for algorithm counters, only VS within 450 ms of the last AS/P will be counted)<br>• 2 consecutive atrial blocked events (2 AP/S without VS)<br>• ≥3/8 atrial cycles without Vs<br>• >15 switches to DDD per hour within the last 24 h | • Extends AVI to 450 ms after a single VS, or after search intervals from 30 s to 20 h (doubling after each failed check)<br>• Intrinsic AVI ≤450 ms for ≥6/8 consecutive VS | • Off |
| Boston Scientific[12] | Rythmiq | • ≥3/11 cycles which R–R >150 ms longer than P–P ("loss of AV synchrony")<br>• Vp might occur during atrial-based mode (see text for details) | • As per AV Search + (it must be programmed "On")<br>• If intrinsic AV conduction for ≥25 cycles and <2/10 last are VP | • Off |
| Medtronic[13] | MVP | • ≥2/4 atrial cycles without VS. There is a backup Vp every other A without V, at 80 ms after the programmed atrial escape interval<br>• In newer models (Azure and Astra series), long PR is also a criterion for reversion, but this feature is deactivated by default[3] | • After 1 min (up to 16 h, doubling after each failed check) a VP is dropped | • On (active 30 min after implantation detection) |
| Sorin[16] | SafeR[a] | • No VS for 3 s<br>• 2 consecutive atrial blocked events (2 AP/S without VS)<br>• 3/12 atrial cycles without VS<br>• 6 consecutive AVI longer than 350 ms (this value might change at high atrial rates)<br>• If several switches to DDD separated <100 AA cycles, "AV block" is declared | • After 12 consecutive VS<br>• After every 100 VP, except if AV conduction is impaired, in which case it will not be checked until next 8:00 am. AV conduction is considered impaired if there are >45 "AV block" during 24 h or >15/24 h × 3 days or >50% DDD for 1 h | • On (active 20 min after implantation detection) |

AP/S, atrial paced or sensed beat; AV, atrioventricular; AVI, atrioventricular interval; MVP, managed ventricular pacing; VP, paced ventricular beat; VS, sensed ventricular beat.
Manufacturers' names are listed in alphabetical order. Figures refer to nominal (standard) settings. Data for Biotronik obtained from teaching documents and advertising material.
[a] Not approved in the United States.

devices use activity sensors based on motion (accelerometers) to measure patient activity and adapt their pacing rate. Besides, some current device families from Boston Scientific (RightRate: Accolade, Essentio, Proponent and Altrua 2) and Sorin (TwinTrace: Reply, Kora and Symphony), as well as legacy Medtronic Kappa, use blended sensors that integrate information from a minute ventilation sensor.[21] This minute ventilation uses sub-threshold pacing pulses to measure cyclic changes in transthoracic impedance to estimate the respiratory rate and adapt their rate accordingly. In any case, activity sensors can increase the pacing rate up to a preset value, usually in the 120–130 bpm range. The operation of the widely extended accelerometer sensor can be verified by "fooling" the sensor by gently tapping on the device for a few seconds.

### 4.2. *Rate smoothing or ventricular rate regulation*

In some circumstances, a sudden drop in heart rate might occur, as in paroxysmal AV block or a pause following atrial tachycardia in bradycardia–tachycardia syndrome. Other rhythm disorders such as atrial fibrillation might be symptomatic from the very irregularity of heart rhythm. Rate smoothing adapts the pacing rate not to a lower fixed rate but to a percentage of the previous R–R interval, thereby softening any abrupt changes in heart rate (Fig. 7).

### 4.3. *Capture control and threshold search*

To measure ventricular thresholds, there must be VP. Therefore, some manufacturers (Boston Scientific, Biotronik) overdrive intrinsic heart rate, up to a maximal predefined value (usually maximum tracking or sensor rate or 110 bpm) (Fig. 8 and Table 1). A backup pace is usually provided to prevent asystole in case of loss of capture during these measurements (Fig. 2).

### 4.4. *Reflex syncope, response to sudden bradycardia*

In vasovagal and carotid sinus syncope, a component of hypotension is added to bradycardia. Thus, a pacemaker

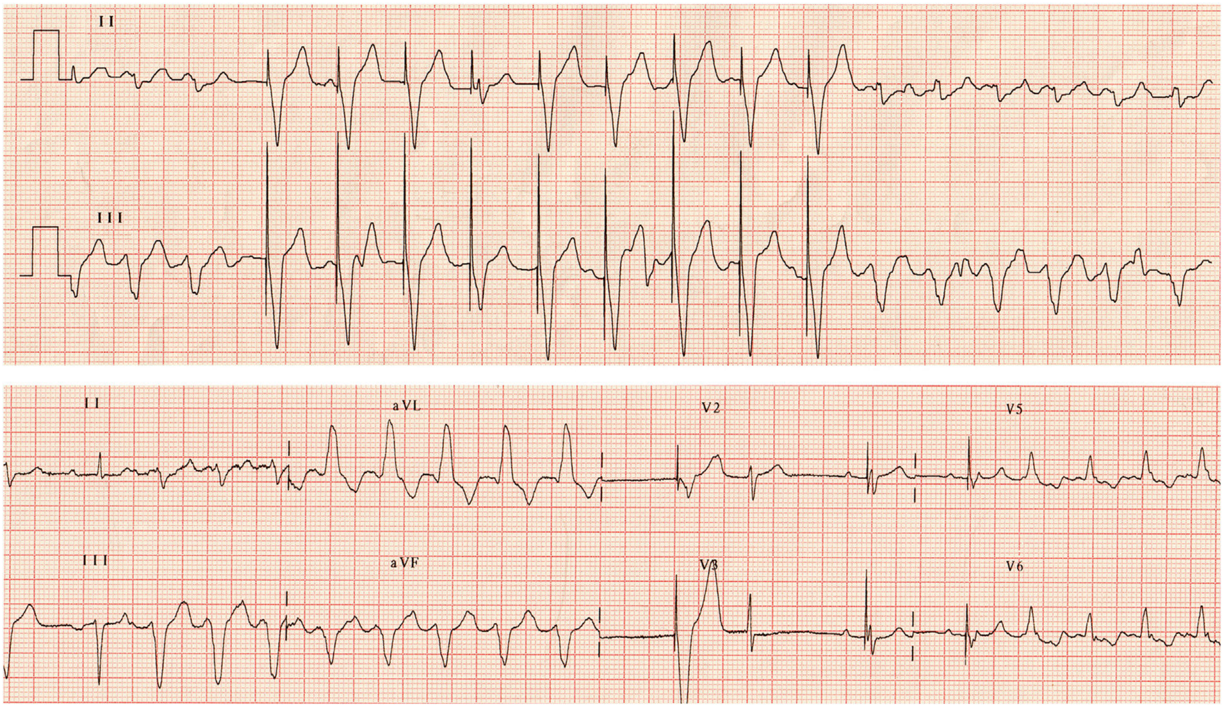


**Fig. 7 – Rate smoothing. The upper tracing shows atrial fibrillation conducted with rapid ventricular rate. A rate smoothing algorithm does not allow the heart rate to drop abruptly, so lower rate limit is temporarily increased to allow minimum deviations from previous heart rate. If such algorithm is turned off, as in the lower tracing, sudden changes in heart rate may occur when pacing only at lower limit. Modified with permission from Ruiz Pizarro et al.[22]**

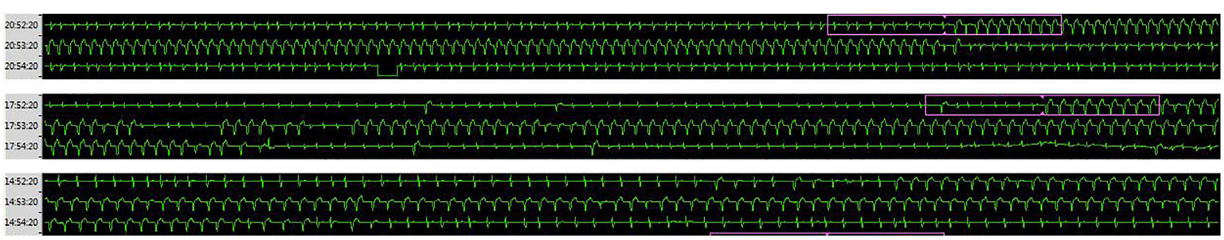


**Fig. 8 – Threshold search in a Boston pacemaker under atrial fibrillation. See rapid ventricular response (narrow, irregular QRS) overdriven by the pacemaker (wider, regular QRS) for some seconds until intrinsic heart rhythm is resumed. These tests occurred every 21 h: see the time stamp on the left, over 3 consecutive days.**

merely working at a lower rate might not overcome the hemodynamic depression and would not avoid syncope. Different algorithms (Table 4) have been devised to detect the sudden bradycardia that precedes syncope and pace at a faster rate (intervention rate) aiming to compensate hypotension with tachycardia and to alleviate symptoms (Fig. 9). With the same spirit but with a different rationale, Biotronik's CLS (Closed Loop Stimulation) does not depend on a previous drop in heart rate. It uses sub-threshold current to measure myocardial inotropy during the cardiac cycle and estimate sympathetic tone, according to which pacing rate is adapted, modifying cardiac output and closing the loop of autonomic feedback.[23]

### 4.5. *Atrial fibrillation prevention algorithms*

After raising a great hype in the 90s, these algorithms fell from widespread use. Their goal is to prevent atrial tachyarrhythmia by keeping a constant pace in the atria: however, their usefulness is yet to be proven.[24] For instance, atrial preference pacing overdrives intrinsic sinus rhythm. After any spontaneous AS, Boston's pacemakers will accelerate heart rhythm by shortening the cardiac cycle by 10 ms, and intrinsic heart rate will be searched by lengthening the cardiac cycle 10 ms every 4 cycles.[12] Abbott, Biotronik (accelerates 8 bpm, searches every 20 cycles),[2] Medtronic (30 ms shortening, searches decreasing 20 ms every 20 cycles),[13] and

**Table 4 – Sudden bradycardia response.**

| Manufacturer | Trade name | Requisites | Intervention |
|---|---|---|---|
| Abbott | No such algorithm; only an adaptation using rate hysteresis and a higher lower rate interval | | |
| Biotronik | *No such algorithm; only Closed Loop Stimulation* | | |
| Boston Scientific[12] | SBR | • Available in DDD pacing mode<br>• As for >1 min followed by >10 bpm drop and atrial pacing for 3 beats<br>• Inhibited during rest (as per minute ventilation sensor) | Pacing at sensor rate or previous atrial rate plus 20 bpm, for 2 min |
| Medtronic[3] | RDR | • Available in DDD, AAI ↔ DDD and DDI modes<br>• Heart rate falls by ≥25 bpm within less than a minute to a minimum rate of 60 bpm | Pacing at 100 bpm for 2 min, then rate is reduced over 5 min until intrinsic rhythm appears or lower rate limit is reached |
| Sorin | Rate acceleration | Not really a dedicated algorithm for sudden bradycardia. Likewise to Abbott's, rate hysteresis is programmed to delay pacing, kicking in at a transient higher-than-normal lower rate interval | |

AS, sensed atrial beat; bpm, beats per minute; RDR, rate drop response; SBR, sudden brady response.
Manufacturers' names are listed in alphabetical order. Figures refer to nominal (standard) settings.

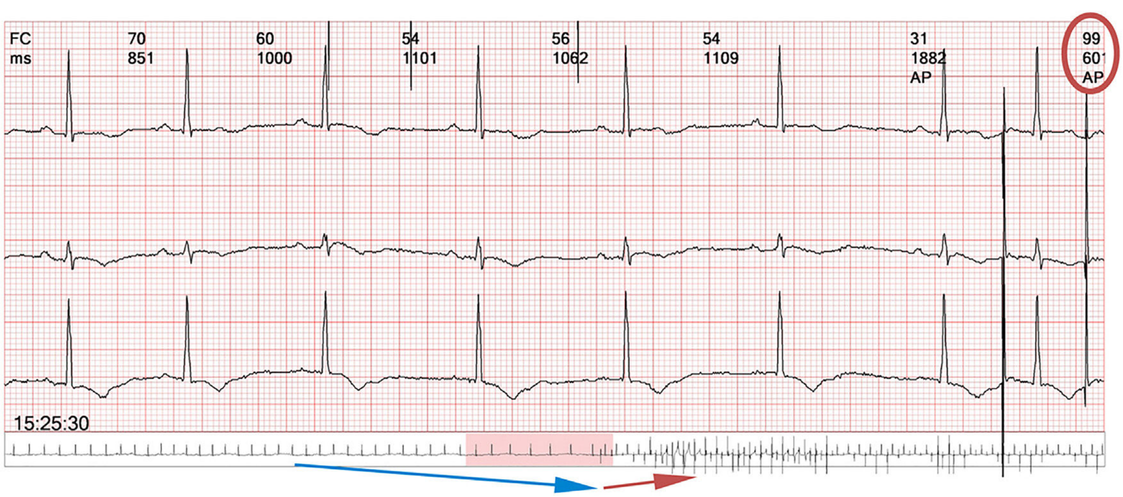


**Fig. 9 – Medtronic Rate Drop Response. The lower rhythm strip shows progressive bradycardia (blue arrow) followed by sudden onset of fast pacing (red arrow). The highlighted epoch (enlarged above) shows how heart rate changes from sinus rhythm at ~50 bpm, to atrial pacing at 100 bpm (red circle).**

Sorin have similar functions. Other algorithms overdrive atrial rhythm after an episode of atrial tachyarrhythmia or prevent post-extrasystolic pause by shortening the cycles following an atrial premature contraction.

### 4.6. *Fallback response or automatic mode switching*

If atrial tachycardia or fibrillation is detected, the pacemaker switches to a non-tracking mode, i.e. VDI/DDI (R). In some cases, to compensate for the reduction in cardiac output secondary to the loss of active atrial emptying, the lower ventricular rate will be increased to 70 bpm (Boston[12]), 80 bpm (Abbott[4]) or 10 bpm over the lower rate limit (Biotronik[2]). This mode switching relies on appropriate detection of atrial tachycardia (also known as atrial high rate episodes, AHRE), since it is triggered by a predefined number of fast sensed atria (over 160[2]–180[12] AS per minute). Thus, if AS is inaccurate, AHRE will not be recognized and irregular tracking and pacing of the atria

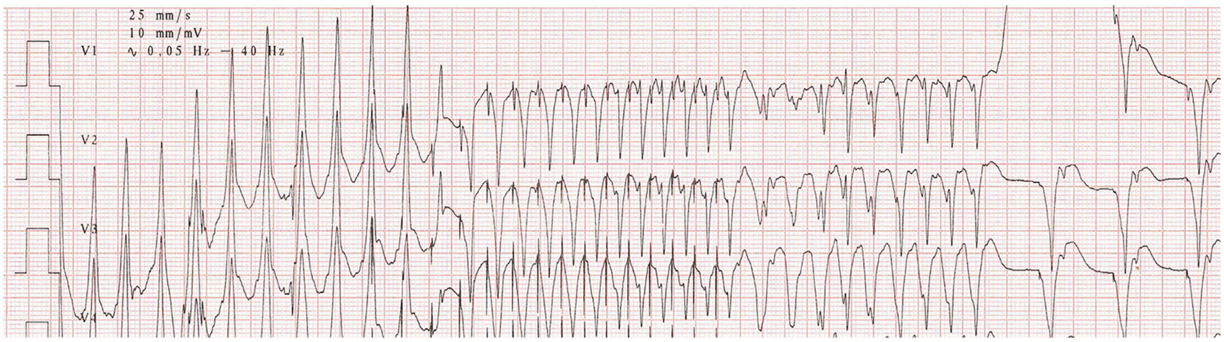


**Fig. 10 – Antitachycardia pacing in an implantable cardioverter defibrillator. The tracing starts with ventricular tachycardia that prompts an anti-tachycardia pacing (ramp, see how the spikes are progressively faster up to a minimum 200 ms), followed by transient acceleration and extinction of the arrhythmia, resuming normal ventricular pacing.**

may occur. This is to be suspected whenever the ECG shows atrial and VP at irregular intervals.

### 4.7. *Antitachycardia pacing*

This behavior belongs to implantable, transvenous, cardiac defibrillators. Ventricular tachycardia can be terminated either by high-energy shocks or by transiently pacing faster than the tachycardia, taking control over it ("entraining") and terminating it. Ventricular spikes can be seen regularly spaced, i.e. pacing at a constant speed (burst), or in decreasing distance, i.e. in accelerating progression (ramp) (Fig. 10). The programming of anti-tachycardia pacing (type, rate, duration, etc.) is outside of the scope of this review. Anyway, it can be suspected when pacing is of short duration and unusually fast (over 150 bpm and even up to 270 bpm).

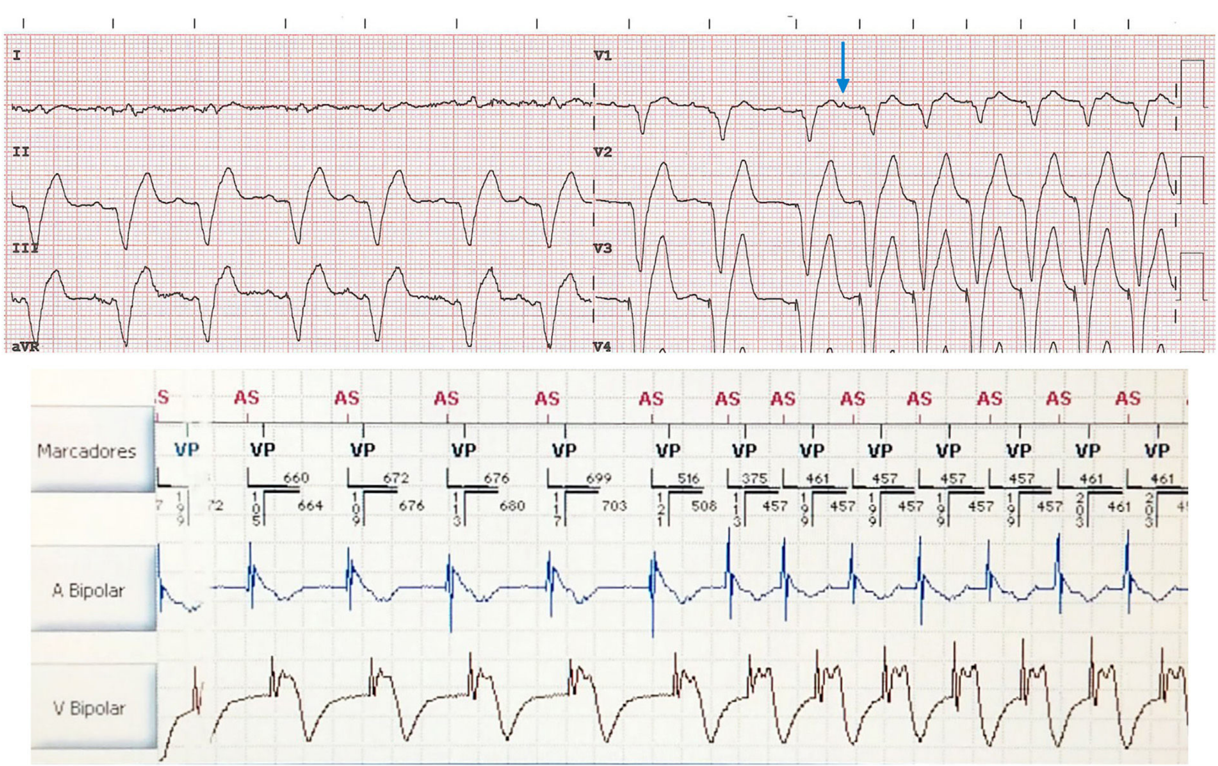


**Fig. 11 – Endless loop tachycardia (ELT), onset. The electrocardiogram strip (above) starts with sinus rhythm and ventricular pacing, followed by a premature atrial contraction (arrow) that is tracked to the ventricles with a longer AVI (199 ms) not to violate the upper rate interval (130 bpm, 460 ms). This ventricular pace propagates retrogradely to the atrium and starts an ELT at the upper rate interval. Device interrogation (below) shows in detail such phenomenon (from upper to lower: marker channel, internal clock timing, atrial electrogram, and ventricular electrogram). This patient was shown to have 1:1 ventriculoatrial conduction at rates over 160 bpm.**

## 5. Low pacing rates or pauses

### 5.1. *Rate hysteresis*

To avoid the deleterious effect of VP, the device allows an intrinsic heart rate lower than the minimum pacing rate. In other words, it will wait for the heart rate to fall to a lower value before pacing, but that pacing will start at a faster rate than the intrinsic one.

### 5.2. *Ventricular pacing reduction algorithms*

They are described in section above.

### 5.3. *Sleep/rest mode*

The lower rate is decreased during some prespecified hours (Biotronik, Medtronic) or under some levels of patient activity (Abbott, Sorin), further mimicking the physiological chronotropic response. This function is programmed off by default. If activated, note that rate is adapted to the internal device clock: should the patient travel to a different time zone, the pacemaker will go to sleep at an inconvenient local time.

### 5.4. *Endless-loop tachycardia treatment*

In endless-loop tachycardia treatment (ELT), a tachycardia is established in the presence of VP, retrograde ventriculoatrial conduction and AS that triggers another VP, perpetuating a reentrant tachycardia where the AV node is the retrograde limb and the pacemaker acts as the antegrade limb. ELT must be suspected in dual-chamber pacemakers when there is VP at upper tracking rate (120–130 bpm) with no AP (Figs. 11 and 12).

To declare an ELT, as opposed to appropriate tracking of sinus tachycardia, the device might cross-check the appropriateness of that tachycardia with the information provided by the activity sensor.[13] Other devices[3,4] use an elegant


**Fig. 12 – Endless loop tachycardia (ELT), termination. Device interrogation (above) shows atrial sensing (AS) tracked to the ventricles (VP) during tachycardia until one of the atria is discarded (AR): the next pacing shows sequential atrioventricular pacing (see text for details). The electrocardiogram (below) shows the characteristic sudden drop in heart rate.**

approach: the timing of a VP is changed to confirm the presence of ventriculoatrial linking and ELT. In either case, the interruption of the antegrade limb will terminate the episode. An AS is not tracked, so a VP is withdrawn,[2,5,12,13] the loop is broken and the heart rhythm drops back to normal. Abbott devices pace sequentially atrium and ventricle, with the AP occurring at 330 ms after the last AS[4] (Fig. 12).

## 6. Failure to sense

### 6.1. *Magnet mode*

A thorough review of pacemaker behavior under magnet application has been published elsewhere.[25] As a summary, a pacemaker responds to magnet application by pacing in asynchronous mode (V00) at a preset rate that depends on the manufacturer and battery status. In other cases, when previously programmed so, magnet application will elicit no apparent response, either because "*Magnet mode*" has been turned off or because the device has been configured to store an internal electrogram. There are a couple of notable exceptions to this rule: as preset, Biotronik devices will function in asynchronous mode only for 10 beats and then return to their normal parameters; and some Abbott and Pacesetter legacy devices (i.e. Microny) have a function named VARIO that performs a threshold test with 16 VP at 100 bpm and constant output followed by 15 VP at 120 bpm with progressive reduction in pacing voltage (Fig. 13).

### 6.2. *Magnetic resonance imaging or electrocautery mode*

Many current pacemakers have a dedicated magnetic resonance imaging, or electrocautery mode. It is essentially an asynchronous mode to prevent interference and oversensing that may lead to inappropriate inhibition or tracking. Upon activation, it can usually be programmed to any manually selected rate. Some devices will revert to previous pacing mode after a preset time, and others will even detect the magnetic field and enter "magnetic resonance imaging mode" only when approaching the gantry.

### 6.3. *Ventricular safety pacing*

A premature ventricular beat coincidental with an AP could elicit a ventricular safety pacing with a pacing spike right on the QRS, giving an impression of undersensing. Nothing farther from the truth: that spike is a safety mechanism already described above.

### 6.4. *Noise reversion*

Different pacemakers recognize patterns of repetitive signals at high frequencies (over 20 Hz for Sorin, 25 Hz for Boston, 100 Hz for Abbott). When such signals are sustained long enough, the device turns to an asynchronous mode at lower rate or sensor rate. The cause and management of such interference, from electromagnetic interference to myopotential oversensing, is beyond the scope of this review.

### 6.5. *Triggered ventricular pacing (VVT mode)*

Cardiac resynchronization therapy devices always try to maximize VP. So, when there is a ventricular premature beat or supraventricular rhythm conducted to the ventricles, there will be VS. Some cardiac resynchronization therapies will pace from the left ventricular lead in response to this VS in the right ventricular channel, willing to resynchronize as much as possible (Fig. 14). It can be differentiated from true failure to sense

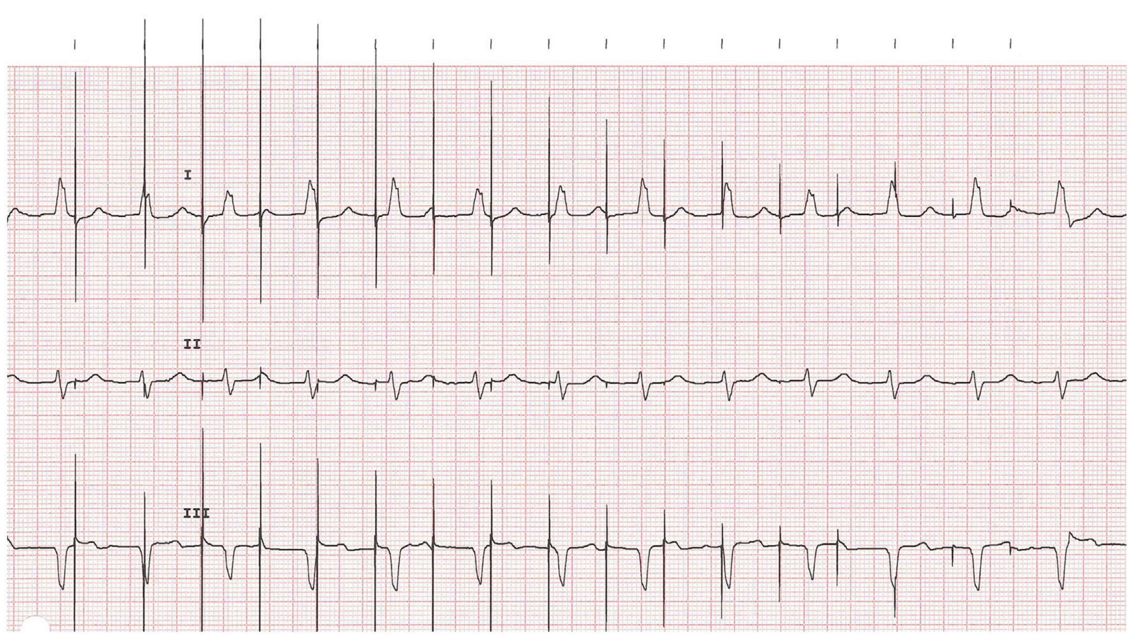


**Fig. 13 – St. Jude VARIO magnet mode (and failure to capture). This electrocardiogram from a Pacesetter pacemaker shows asynchronous pacing spikes at 100 bpm followed by others at 120 bpm with a decreasing amplitude. Plus, this patient had a malfunctioning lead with failure to capture.**

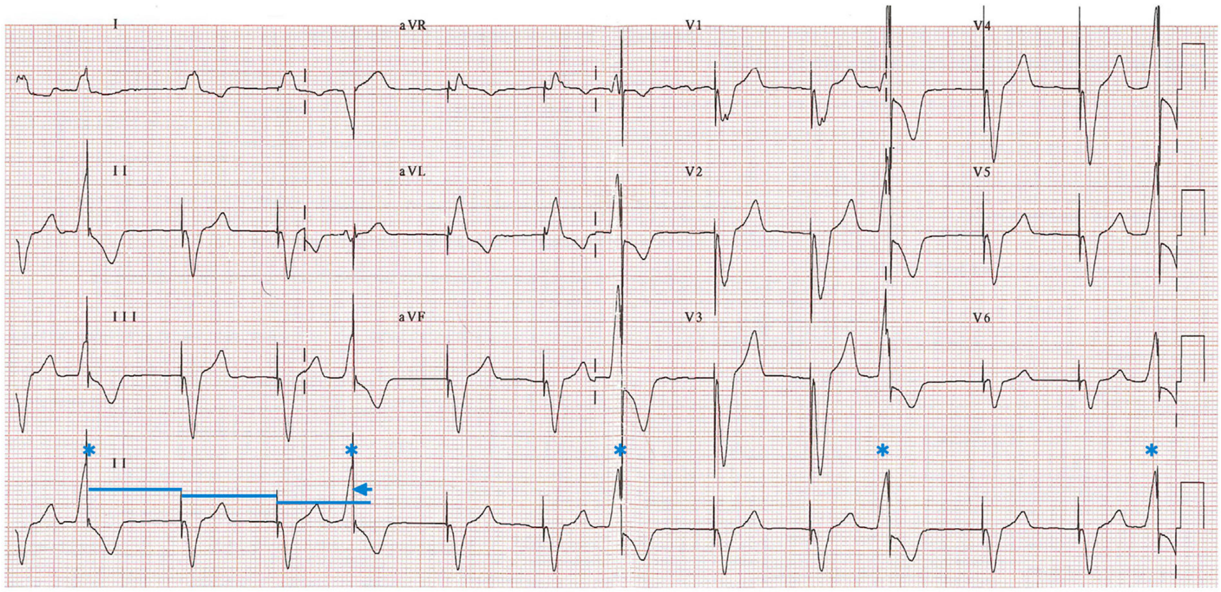


**Fig. 14 – Triggered ventricular pacing. The patient had a cardiac resynchronization therapy functioning in VVIR mode at ~70 bpm with high density ventricular premature beats (asterisks). The cardiac resynchronization therapy responded to sensing of every ventricular premature beat by pacing from the left ventricular lead: this triggered pacing occurs, therefore, earlier than expected (arrow). Reproduced with permission from Fernández-Vega et al.[26]**

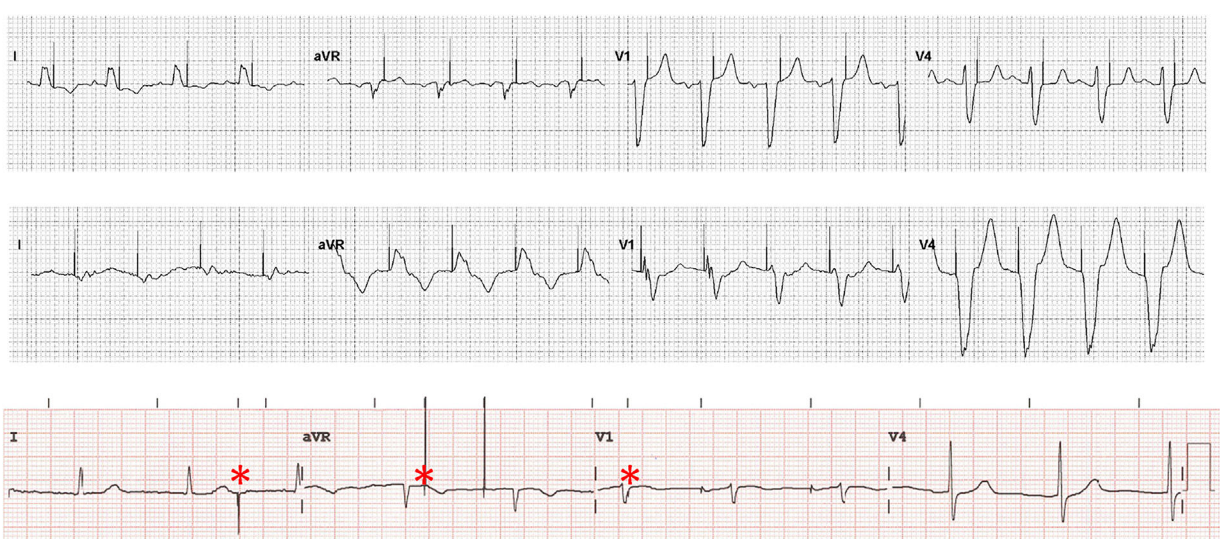


**Fig. 15 – False pacing spikes. The electrocardiogram (ECG) of a patient with a single-chamber Biotronik Lumax ICD showed pacing spikes after every QRS (upper ECG); a recording was later repeated, activating manually ventricular pacing, with a clearly different QRS morphology (middle ECG). In this case, the false pacing spikes were due to the home monitoring intrathoracic measurement that sends 1024 sub-threshold pulses every hour, 100 ms after every ventricular event (sensed or paced). The lower ECG shows a trace of a patient with a dual-chamber Sorin Kora: AAI-based pacing can be observed, with spikes randomly distributed (asterisks) throughout the tracing. Simultaneous device interrogation showed no pacing other than atrial.**

because the pacing spike appears earlier than expected at the programmed pacing rate.

### 6.6. *False pacing spikes. Transthoracic impedance – heart failure monitors*

Digital ECG recorders have band-pass filters to remove baseline respiration and movement wander, myopotentials and electrical powerline noise. However, these filters also suppress pacemaker signals, so current ECGs do not represent "true" pacing spikes but they rather depict an artificial pacing spike when they find a signal with a particular bandwidth, voltage, and duration criteria.[27] Similarly, any artifact meeting such criteria will be signaled as a pacing stimulus, which can be a nuisance to the clinician. Some pacemakers have features that use sub-threshold pulses to obtain information about the device or the patient; such pulses might be recorded in the ECG, showing a regular though un-understandable behavior with the appearance of failure to sense/capture (Fig. 15). In other cases, just random, ambient noise can be picked by the ECG recorder. There is no common feature or pattern that can be recognized in these cases, but we must be aware of such possibility.

## 7. Failure to capture

### 7.1. *Threshold search*

As explained before, some pacemakers perform a regular assessment of their capture threshold (Table 1). By definition, this means that some pacing artifacts will not capture, but usually, a backup pace will then be provided. However, Medtronic cardiac resynchronization therapy devices are somewhat different. They assess the capture threshold daily using iterations of three support pulses followed by one test pulse. Right ventricular test pulses are followed 90 ms later by a backup pulse to ensure capture, as opposed to left ventricular test pulses, which lack such backup.[14] Therefore, loss of capture during the assessment of left ventricular threshold will cause a pause in the absence of intrinsic atrioventricular conduction or escape rhythm.

## 8. Conclusions

This review tries to cover the different pacemaker algorithms that may mimic a pacemaker failure when its operation is observed in a conventional ECG, Holter or telemetry monitoring. We believe that it may help the clinician to understand the apparently atypical behavior associated with these algorithms, and distinguish it from true device dysfunctions. However, bear in mind that some of the algorithm parameters (timings, intervals) can be manually modified, and new devices and firmware are released every year, impeding their recognition. Nevertheless, the bottom line is that pseudodysfunctions always follow the same patterns, as opposed to real malfunctions, which are genuinely chaotic.

## 9. Conflicts of interest

None relevant to this article.

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