HK-IN-PACE
Heart Rhythm Refresher Course 2013
Module 1 – Cardiac Pacing:
Concepts and Practice

Pacemaker Timing:
Theories and Real-Life

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# Pacemaker Mode Nomenclature

<table>
<thead>
<tr>
<th>I Chamber Paced</th>
<th>II Chamber Sensed</th>
<th>III Response to Sensing</th>
<th>IV Programmable Functions/Rate Modulation</th>
<th>V Antitachy Function(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V: Ventricle</td>
<td>V: Ventricle</td>
<td>T: Triggered</td>
<td>P: Simple programmable</td>
<td>P: Pace</td>
</tr>
<tr>
<td>D: Dual (A+V)</td>
<td>D: Dual (A+V)</td>
<td>D: Dual (T+I)</td>
<td>C: Communicating</td>
<td>D: Dual (P+S)</td>
</tr>
<tr>
<td>O: None</td>
<td>O: None</td>
<td>O: None</td>
<td>R: Rate modulating</td>
<td>O: None</td>
</tr>
<tr>
<td>S: Single (A or V)</td>
<td>S: Single (A or V)</td>
<td>O: None</td>
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</tbody>
</table>
Single Chamber Timing Cycle

• Lower rate limit (LRL)
• Upper rate limit (URL)
  – Maximum sensor rate (MSR)
• Refractory period
• Blanking period
Lower Rate Limit (LRL)

• Defines the lowest rate the pacemaker will pace
Maximum Sensor Rate (MSR)

- Defines the shortest interval (highest rate) the pacemaker can pace as dictated by the sensor (AAIR, VVIR modes)

Lower Rate Interval

Upper Sensor Rate Interval

Blanking Period
Refractory Period

VVIR / 60 / 120
Refractory Period

- **Refractory period**
  - Interval during which the pacemaker does not respond to intrinsic signals
  - Starts with a paced or sensed event and times out
  - Programmable
  - Two phases
    - **Absolute** (the pacemaker does not sense intrinsic signals)
      - **Blanking Period**
    - **Relative** (the pacemaker senses but does not respond to intrinsic events)
Refractory Period

- Interval initiated by a paced or sensed event
- Designed to prevent inhibition by cardiac or non-cardiac events
Blanking Period

• The first phase of the refractory period
• Pacemaker is “blind” to any activity
• Prevents over-sensing pacing stimulus and/or cross talk with the other chamber

Lower Rate Interval

VP

VP

Blanking Period
Refractory Period

VVI / 60
Alert Period

- The interval during which the pacemaker “sees” cardiac signals and responds to them
- The period between refractory periods
- Not directly programmable
  - Could be indirectly modified by adjusting the refractory period
Ventricular refractory period (VRP)

Example

VVI Mode
VPC in the VRP is not sensed (ignored) → does not reset the timing cycle
Pacing continues at its own rate driven by LRL
The ventricular channel is “Blind” – It does not sense /respond to any intrinsic signals To prevent over-sensing of pacing stimuli or cross-talk with signals from another chamber In dual chamber system
Post atrial blanking/refractory period

AAI Pacing

(Postatrrial Atrial) Blanking Period  (Postatrrial Atrial) Refractory Period

Lower rate interval
Blanking period in VOO Mode

- Asynchronous pacing delivers output regardless of intrinsic activity

Lower Rate Interval

Blanking Period

VOO / 60
Dual Chamber Timing Cycle
Four “Faces” of Dual Chamber Pacing

- Atrial Pace, Ventricular Pace (AP/VP)

Rate = 60 bpm / 1000 ms
A-A = 1000 ms
Four “Faces” of Dual Chamber Pacing

- Atrial Pace, Ventricular Sense (AP/VS)

Rate = 60 ppm / 1000 ms
A-A = 1000 ms
Four “Faces” of Dual Chamber Pacing

- Atrial Sense, Ventricular Pace (AS/ VP)

Rate (sinus driven) = 70 bpm / 857 ms
A-A = 857 ms
Four “Faces” of Dual Chamber Pacing

- Atrial Sense, Ventricular Sense (AS/VS)

Rate (sinus driven) = 70 bpm / 857 ms
Spontaneous conduction at 150 ms
A-A = 857 ms
Dual Chamber Timing Cycle

- Lower rate limit (LRL)
- Upper rate limit (URL)
  - Maximum tracking rate (MTR)
  - Maximum sensor rate (MSR)
- AV and VA interval
- Refractory period
- Blanking period
**AV Intervals (AVI)**

- Interval between a sensed/paced atrial event to the next V pacing event
  
  - Separately programmable AV intervals – SAV / PAV

  ![Diagram of AV Intervals](image)

  - Paced AV usually ~ 30ms longer than sensed AV AV

  - SAV = Sensed AVI; PAV = Paced AVI

  - **DDD 60 / 120**
Atrial Escape Interval (V-A interval)

- The interval initiated by a paced or sensed ventricular event to the next atrial event

**Lower Rate Interval**

LRL interval = 1000ms  
AVI = 200ms

E.g.  
VA Interval = LRL interval – AVI  
= 1000-200ms  
= 800ms

**Example Configuration**

- DDD 60 / 120
- PAV 200 ms; V-A 800 ms
Dual Chamber - Refractory Periods

**VRP**: prevents over-sensing of intrinsic signals (e.g. T waves over-sensing) → ↓ pacing inhibition

**PVARP**: prevents sensing of retrograde P waves → ↓ pacemaker mediated tachycardia

**VRP/ PVARP** – both initiated by a sensed or paced ventricular event
Dual Chamber - Blanking Periods

First portion of the refractory period during which sensing circuitry is disabled

Atrial Blanking (Nonprogrammable)

Post Atrial Ventricular Blanking (PAVB)

Post Ventricular Atrial Blanking (PVAB)

Ventricular Blanking (Nonprogrammable)

PVAB – Prevents atrial channel from sensing ventricular event
PAVB – Prevents ventricular channel from sensing atrial event
→ Prevents cross talk inhibition of pacing
TARP – Total Atrial Refractory Period

TARP = AV Interval + PVARP
Dual Chamber Timing Cycle

- AV delay
- PVAB
- Total Atrial Refractory Period

- Ventricular refractory
- R-wave alert period
- Absolute portion of PVARP
- Far-field event

- Atrial channel
- Ventricular channel

- Vent blanking
- Crosstalk detection window (VSS)
- Absolute portion of ventricular refractory
- R-wave alert period
Clinical Relevance 1

Why does the pacemaker pace at a lower-than-expected rate?

Battery depletion/PPM malfunction

**Timing Cycle Related Causes:**

- Sleep rate (pacing rate set < LRL during sleep)
- Atrial based timing
- Non-atrial tracking mode (e.g. DDI)
- Rate Hysteresis
- Upper Rate Behaviour - Pacemaker Wenckebach or 2:1 Block
Atrial rate = Constant = LRL
Ventricular rate could be > or < LRL
PPM can pace at a rate above or below LRL

AA Interval = constant regardless of ventricular conduction
VA variable
Sensed ventricular event in AVI → inhibits V pacing, but does not rest timing cycle

A to A = 1000 ms
AV = 200
V-A = 800

A to A = 1000 ms
AV = 150
V-A = 850

AR=950ms=63bpm
RR=1050ms=57bpm

LRL = 1000ms = 60bpm
Ventricular Based Timing

VA = Constant
AA = Variable
Sensed ventricular event in AVI → inhibits V pacing and resets timing cycle (VA)

A to A = 1000 ms (60bpm)  A to A = 950 ms (63bpm)

V-V Timing

AV = 200  V-A = 800  AV = 150  V-A = 800  AV = 200

RR=950ms=63bpm  RR=1000ms=60bpm

LRL = 1000ms = 60bpm

Atrial rate variable = or > LRL
Ventricular rate could be = or > LRL
PPM can pace at a rate = or above LRL
Dual Chamber Timing Cycle

Table 7.3 Summary of the timing systems in the most recent generation of pacemakers from each company

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Timing system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biotronik</td>
<td>In DDI mode the pacemaker uses ventricular-based timing and therefore R sensing which truncates the programmed AVI would start a VA timer. The result would be a rate of 62 or 63. When programmed to DDD or DDDR, the generators use atrial-based timing. Therefore, the lower rate timer and TARP begin with A sense, A pace or PVC sense. Atrial pacing is accomplished by expiration of the lower rate timer (there is no VA timer.)</td>
</tr>
<tr>
<td>Boston Scientific</td>
<td>If the ventricle is being paced, the escape interval timing occurs from one ventricular event to the next. If a sensed ventricular event occurs, i.e., the AV interval is truncated by an intrinsic R, the timing system switches to one of atrial-based timing to maintain rates that are true to the programmed rates</td>
</tr>
<tr>
<td>Medtronic</td>
<td>A-to-A timing is used on all current bradycardia treatment devices (IPGs). The pacemaker will lengthen the subsequent V-A timing to adjust for a prior shortened A-V delay due to native R waves being sensed or due to rate-adaptive AV adjustments, etc. This strategy will, by design, provide consistent A-to-A intervals at the expense of producing V-to-V delays that may be somewhat slower than the programmed lower rate [e.g., V-to-V rate may be as slow as 60 000/(lower rate interval + PAV – measured AV)]</td>
</tr>
<tr>
<td>Sorin</td>
<td>Modified atrial based timing system; basic intervals are determined by the atrial channel in tracking modes. PVCs (ventricular events not preceded by an atrial event) will reset all clocks as well as automatically add a nonprogrammable 500-ms atrial refractory period to prevent pacemaker-mediated tachycardia.</td>
</tr>
<tr>
<td>St Jude Medical</td>
<td>Ventricular based timing if: VDD; DDI; DDD when PV &gt; MTR; DDD with safety pacing; VDD/DDD with PVC. Modified* atrial-based timing if: DDD; DDD with PV &lt; MTR or AV events; DOO (*change to ventricular-based timing when atrial events are faster than MTR but still in alert)</td>
</tr>
</tbody>
</table>
Non-atrial tracking mode (e.g. DDI)

Pacemaker can pace at a rate < LRL

**DDI Mode**
(Like a DDD mode with no atrial tracking)

LRL = 1000ms

VA 500ms + AVI 200ms = 700ms
→ Still < LRL interval of 1000ms
→ Cannot violate LRL to pace at a slower rate
Rate Hysteresis

Pacemaker can pace at a rate < LRL

• A function that allows intrinsic rhythm < LRL to inhibit pacing
  – Encouraging native cardiac rhythm

• Example
  – LRL = 70 ppm
  – Hysteresis rate = 60 bpm
  – PPM searches for intrinsic activity in an extended alert period cyclically
  – If intrinsic rate > 60 bpm → pacemaker will not pace in
  – If intrinsic rate < 60 bpm → Pace at 70 bpm again until intrinsic rate \( \geq 60 \text{ bpm} \) again → Hysteresis
Hysteresis

- Allows the rate to fall below the programmed lower rate following an intrinsic beat.

Lower Rate Interval-60 ppm

Hysteresis Rate-50 ppm
Rate hysteresis

Not useful for patients
- Have very slow intrinsic rhythms
- Cannot tolerate pacing below the base rate
- Are pacemaker dependent
- On CRT
Upper Rate Behavior
Total Atrial Refractory Period (TARP)

- TARP = AVI + PVARP
- MTR = Maximum Tracking Rate/Upper Tracking Rate

If MTR Interval < TARP → Pacemaker Wenckebach
If MTR Interval >= TARP → Pacemaker 2:1 AVB
Pacemaker Wenckebach
(when MTR interval > TARP)

Prolongs the SAV until upper rate limit expires

Lower Rate Interval

Upper Tracking Rate

P Wave Blocked (unsensed or unused)

DDD
Sinus rate = 109 bpm (550 ms)
MTR = 100 ppm (600 ms)
SAV = 200 ms

LR = 60 bpm (1000 ms)
PAV = 230 ms
PVARP = 300 ms
TARP = 500/530ms
Pacemaker Wenckebach

A-V Interval gradually prolongs until AV Block
Pacemaker 2:1 Block
(When MTR interval < TARP)

• Every other P wave falls into refractory and does not restart the timing interval

Sinus rate = 150 bpm (450 ms)
PVARP = 300 ms SAV = 200 ms
TARP = 500 ms
MTR = 160 bpm (375 ms)
Pacemaker 2:1 Block

Only every other atrial event is tracked
Wenckebach vs. 2:1 Block

- If the MTR interval > TARP, the pacemaker will exhibit Wenckebach behavior first

- If the TARP is > MTR upper interval ➔ Pacemaker 2:1 block will occur
Clinical Relevance 2
Wenckebach Cycle Calculation

• What will the upper rate behavior of this pacemaker be?

• LRL = 60 bpm
• MTR = 120 bpm (MTR interval = 500 ms)
• PAV = 230 ms
• SAV = 200 ms
• PVARP = 350 ms
Wenckebach vs. 2:1 Block – Solution

- MTR Interval = 500ms
- TARP = SAV + PVARP = 550ms

- TARP > MTR Interval ➜ Pacemaker 2:1 block
Wenckebach vs. 2:1 Block – What Will Happen First?

• What will the upper rate behavior of this pacemaker be?

• LRL = 60 ppm
• MTR = 110 ppm
• PAV = 150 ms
• SAV = 120 ms
• PVARP = 350 ms
Wenckebach vs. 2:1 Block – Solution

- MTR Interval = 545ms
- TARP = SAV + PVARP = 470ms

- MTR Interval > TARP  ➔  Pacemaker Wenckebach
Upper Rate Behaviour

- When atrial rate > MTR (and MTR interval > TARP) → Pacemaker Wenckebach

- When atrial rates > TARP → Pacemaker 2:1 block
What Can We Do to Make Wenckebach Occur First?

• Shorten or reduce the TARP by:
  – Shortening the PVARP
  – Shortening the SAV
  – Programming Rate Adaptive-AVI (shortens AVI in response to increase in HR)
Pacemaker Wenckebach $\rightarrow$ 2:1 Block

Pacemaker Wenckebach Transition into Pacemaker 2:1 Block as atrial rate increases
Clinical Relevance 3

Why does the pacemaker pace at a higher-than-expected rate?

Pacemaker malfunction/Rate-drop response
Atrial over-sensing $\rightarrow$ inappropriate atrial tracking/ Magnet application/ Preferential atrial pacing (e.g. AF suppression algorithm)

**Timing cycle related causes:**
- Atrial or ventricular based timing
- Sensor response
- Atrial tracking
- Rate adaptive AVI/ PVARP
Maximum Tracking Rate (MTR)

- The maximum rate the ventricle can be paced in response to sensed atrial events.

**DDD 60 / 100 (upper tracking rate)**

**Sinus rate: 100 bpm**
Maximum Sensor Rate (MSR)

- In rate responsive modes, the Maximum Sensor Rate (MSR) provides the limit for sensor-indicated pacing.
Rate Response of DDDR Pacemaker

- Exercise
- Rest

- Maximum sensor rate
- Maximum tracking rate
- Sensor-driven rate
- P-tracking
- Increasing workload

Rate, ppm

Time, min
Titration of sensor slope according to physiological demand

Fig. 9.28: Schematic depiction of the clinical effect of programming different rate response values. If too aggressive, the patient will achieve faster rates more quickly and perhaps faster than desirable. If not programmed aggressively enough, an appropriately fast rate response will not be achieved. (Reproduced from SJM p 8.5 courtesy of and copyrighted by St Jude Medical.)

Fig. 9.29: Various example of programming the (A) reaction or acceleration times and (B) the recovery or deceleration times of a rate-adaptive sensor. (Reproduced from SJM p 8.5 courtesy of and copyrighted by St Jude Medical.)
Rate adaptive AVI

AVI shortens in response to increase in heart rate
Rate Adaptive PVARP

- PVARP will shorten as heart rate increases

Long PVARP with little activity (Rate 63 ppm)

Shorter PVARP with increased activity (Rate 86 ppm)
Clinical Relevance 4: Crosstalk

- Crosstalk is the sensing of a pacing stimulus delivered in the opposite chamber, which results in undesirable pacemaker response, e.g., false inhibition

A pacing → crosstalk → inhibition of V pacing
Clinical Relevance 4
How to prevent long pause during cross talk: Ventricular Safety Pacing

• Following an atrial paced event, a ventricular safety pace interval is initiated
  – If a ventricular sense occurs during the safety pace window, a pacing pulse is delivered at an abbreviated interval (110 ms)
Ventricular Safety Pacing

Safety pacing if any ventricular event/noise is sensed within the 110ms safety pace window

110 ms
Ventricular Safety Pacing
Clinical Relevance 5
How can we minimize crosstalk

- Prolongs the blanking period to prevent far-field sensing (e.g. Far Field R wave)
Pacemaker Mediated Tachycardia (PMT)

• PMT is a paced rhythm, usually rapid, which is sustained by ventricular events conducted retrogradely (i.e., backwards) to the atria.

• PMT can occur with loss of AV synchrony caused by:
  – PVC
  – Atrial non-capture
  – Atrial undersensing
  – Atrial oversensing
PMT

1. Loss Of A-V Synchrony Due To A PVC
2. Sensed Retrograde Activation
3. A-V Interval Initiated
4. Prolongation Of A-V Interval
5. Ventricular Pacing Synchronized To Retrograde P-Waves
PMT
Clinical Relevance 5

• How can we prevent and terminate PMT by programming of the timing cycle?
Solution: PMT Prevention

- PVARP prolongation post PVC
  - PVARP is extended to 400 ms
  - The retrograde A will not be sensed and tracked
  - Prevents PMT
PMT Prevention

• How long should PVARP be programmed?
  – Do a retrograde VA conduction test first
  – Measure the VA interval
  – PVARP should be longer than intrinsic retrograde VA interval in order to prevent PMT
Solution: PMT termination

- Designed to interrupt a Pacemaker-Mediated Tachycardia

PVARP prolongation → Retrograde A not sensed
→ PMT terminated
Clinical relevance 6

• What will be the problem if PVARP is too long?
Repetitive Non-reentrant VA Synchronous Rhythm (RNRVAS)

When PVARP is too long
- Retrograde A not sensed (functional atrial undersensing)
- Then next A pace could not capture (as A still refractory (functional atrial noncapture)
RNRVAS

Mechanism

**Intact retrograde VA conduction**

**Functional atrial undersensing** (as retrograde P wave coincides with PVARP)

**Functional atrial noncapture** (as atrial output coincides with physiologic refractory period of atrial myocardium)

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**PVARP**
- Rate 90 (660 ms)
- AV Delay 300 ms
- Retrograde 200 ms
- PVARP 300 ms
- Physiol ARP 200 ms
PVC initiating RNRVAS

LOWER RATE INTERVAL = 750 ms
AV DELAY = 250 ms
PVARP = 400 ms
Clinical Relevance 7

• How can we program the timing cycle to overcome RNRVAS?

Management
- Prolongation of the atrial escape interval to allow atrial myocardium time to recover
- Decrease the lower base rate (increase lower rate interval)
- Decrease the sensor-driven upper rate
- Shorten the AV delay

Algorithms
- Prolongation of the atrial escape interval following a PVC with +PVARP on PVC
- Synchronous atrial pacing upon detection of a VPC (primarily designed to prevent endless loop tachycardia)
- Noncompetitive atrial pacing
- Automatic shortening of the AV delay
  - Rate-adaptive AV delay
  - AV conduction search
- Automatic endless loop tachycardia termination
Timing Cycle in CRT

A

B

C
Common cause of CRT non-response

Loss of Biventricular Pacing

VPC → The next P falls within PVARP → Loss of atrial tracking → Intrinsic AV conduction with prolonged PR → The next P falls within PVARP again → Loss of atrial tracking → Loss of Bi-ventricular pacing
iTARP – Implied TARP

iTARP = implied AV + Interventricular conduction delay (IVCD) + PVARP
Clinical Relevance 8

• How can we maximize biventricular pacing by programming PVARP?
Atrial Tracking Recovery

Shortens the PVARP to restore atrial tracking and Bi-ventricular pacing
Timing Cycle in Real Life

• Apply what you’ve learnt in clinical practice
Ventricular Safety Pacing caused by VPC in the safety pace window (110ms phenomenon)
Is This Normal Device Operation?

Pacemaker Wenckebach
Pacemaker Wenckebach turning into Pacemaker 2:1 block as atrial rate exceeds TARP
References


Thank you very much

Compliments: Medtronic