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Different Automatic Mode Switching in DDDR Pacemakers

Maurizio Santomauro MD¹, Carlo Duilio MD¹, Carla Riganti MD¹,
Paolo Di Mauro MD¹, Gennaro Iapicca MD¹, Luca Auricchio Eng²,
Alessio Borrelli MD³ and Pasquale Perrone Filardi MD¹

¹*Department of Medicine, Cardiology and Immunology,
Federico II School of Medicine University of Naples, Naples*

²*Boston Scientific, CRM Department, Milan,*

³*Department of Cardiology, Humanitas Hospital, Bergamo,
Italy*

1. Introduction

Mode-switching algorithms are designed to alleviate symptoms related to tracking of atrial arrhythmias, that may result in inappropriately rapid or irregular ventricular pacing[1-19]. The ideal mode-switching algorithm should discriminate sinus tachycardia, a rhythm that should be tracked, from pathological atrial arrhythmias, rhythms that generally should not be tracked. In order to minimize symptoms related to the occurrence of atrial arrhythmias, the mode-switching algorithm should change quickly from a tracking to a non-tracking mode at the onset of the pathological atrial rhythm and remains in this mode until the arrhythmia terminates. Once sinus rhythm has been restored, the pacemaker should revert quickly to the normal atrial tracking mode.

There are several potential causes of symptoms that relate to mode switching. First, an irregular paced ventricular intervals at the onset of an atrial arrhythmia before conversion to a non-tracking mode. Second, failure of the device to convert to a non-tracking mode because of intermittent undersensing of the atrial electrocardiogram may result in continued irregular or rapid ventricular pacing [20]. Third, inappropriate reversion to a tracking mode despite persistence of an atrial arrhythmia may also be caused by intermittent undersensing of the atrial electrocardiogram. Fourth, an overly sensitive mode-switching algorithm may result in loss of atrio-ventricular (AV) synchrony in sinus rhythm [2,11,17,19]. Finally, intrinsic AV conduction of an atrial arrhythmia may produce symptoms that are unrelated to the pacemaker [21]. Although all manufacturers of dual chamber pacemakers offer devices that provide mechanisms for managing the occurrence of atrial arrhythmias, the mode-switching algorithms that are available differ significantly in their sensitivity, specificity, and speed of mode conversion at the onset and termination of atrial arrhythmias. There are potential compromises between sensitivity and specificity with these algorithms, the balance of which may determine the frequency of arrhythmia-related symptoms. Atrial-based pacing is associated with a risk of developing atrial fibrillation lower than ventricular-based pacing for patients with sinus node dysfunction [22-25].

Although AAI(R) pacing provides AV synchrony without tracking of atrial arrhythmias, this mode is not appropriate for patients with impaired AV conduction. For individuals in whom AV conduction is unreliable, atrial-based pacing requires a dual chamber pacemaker to be implanted. Although the physiological benefits of atrio-ventricular synchrony are well documented in these patients, tracking of atrial tachy-arrhythmias can lead to rapid ventricular pacing and the occurrence of palpitation, dyspnea, chest pain, or lightheadedness. Although reprogramming to a non-tracking mode (such as DVI, DDI or DDIR) prevents this clinical event, these modes do not provide appropriate AV synchrony if the sinus rate exceeds the programmed lower rate. (26-37) Limitation of the upper tracking rate only partly addresses this problem and may compromise exercise capacity or lead to symptoms from pacemaker Wenckebach behaviour at relatively slow rates. In response to this clinical dilemma, a variety of mode-switching algorithms has been devised that are meant to prevent tracking of pathological atrial tachy-arrhythmias while allowing ventricular pacing that is synchronous with the atrial electrocardiogram during sinus rhythm [17-19]. These algorithms differ in the criteria that must be satisfied at the onset of a tachy-arrhythmia to trigger a change from a tracking to a non-tracking mode as well as the conditions for return to a normal tracking operation upon arrhythmia termination. As a result, each algorithm provides its own balance in terms of sensitivity and specificity for the accurate detection of atrial arrhythmias. If the criteria that must be satisfied to initiate mode switching are too strict, inappropriate tracking of atrial arrhythmias may occur. In contrast, if the criteria are too sensitive, mode switching may occur in response to single atrial extrasystoles, myopotentials, or far-field signals (26).

The hemodynamic and clinical usefulness of automatic mode switching (AMS) to control the ventricular pacing rate of dual chamber pacemakers was reviewed previously (38-63). The clinical behavior and programmability of the various types of AMS algorithms are reviewed in this part of the manuscript. Current AMS algorithms can be classified according to the way atrial tachy-arrhythmias are detected:

1. "Rate cut-off" criterion: the sensed atrial (As) rate exceeds a programmable value;
2. "Running average rate" criterion: the atrial rate exceeds a mean atrial rate calculated by the pacemaker from the duration of the preceding atrial rate;
3. "Sensor-determined" physiological rate to distinguish sinus rhythm from atrial tachy-arrhythmia;
4. Complex algorithms that combine one or more of the above criteria, with or without additional methods such as examining the atrio-ventricular (AV) relationship.

2. Types of AMS

This discussion focuses mainly on atrial tachy-arrhythmia detection by algorithms developed by several major pacemaker companies to illustrate their complexity and evaluation. Different device behaviors in switching mode are shown in Table I while different algorithm mode termination are shown in Table II.

2.1 Boston scientific / guidant - Atrial Tachy Response (ATR)

The Boston Scientific devices offer two methods of handling atrial tachyarrhythmia, a true automatic mode switch (ATR) that switches mode when consecutive atrial cycles fall below a programmable cutoff and a fast-switch algorithm (AFR) that responded rapidly to the onset of atrial tachyarrhythmia for example in case of atrial flutter.

The ATR function in the Altrua (Boston Scientific Natick, MA, USA) and Insignia pacemakers (Guidant Inc., St. Paul, MN, USA) uses a rate cutoff and counter-based algorithm. Atrial events above the atrial tachyarrhythmia detection rate start the algorithm. When the entry count (programmable number of cycles above the trigger rate) has been satisfied (+1 beat for beats above the trigger rate, and -1 beat for beats below the trigger rate until the entry count is met), Duration (programmable number of ventricular beats at MTR) will begin.

During Duration the device counts atrial intervals (for the atrial trigger rate) and V-V cycles (for number of Duration beats). If counter is still above zero at the end of Duration, device will go in fallback mode (DDI(R) or VDI(R)) and mode switch.

After fallback rate decrease to LRL or sensor indicated rate for the fallback time (programmable) until end of the ATR episode that occurs when atrial exit count (programmable number of cycles below the trigger rate) goes zero.

The AFR algorithm is designed to prevent pacing in to the atrial vulnerable period and provide immediate dissociation to the atrium and ventricle for atrial rates higher than the AFR trigger rate. When an atrial event is detected inside the PVARP a programmable interval will be set and atrial events inside the AFR interval will be classified as refractory sensed and will not be tracked.

If ATR is programmed ON with AFR, an ATR episode may also be initiated if the atrial tachy is fast and sustained enough to fulfill the ART criteria.

Normal dual-chamber operation resumes immediately when both the PVARP and AFR windows have expired without P-waves being sensed within them.

2.2 Medtronic - Auto Mode Switching algorithm

Mode Switch has a programmable Detect Rate that specifies when to switch modes and a Detect Duration setting to screen out short tachycardia episodes. It also has a Programmable Blanked Flutter Search setting to switch modes if 2:1 blanking of a rapid atrial arrhythmia is detected. The pacemaker defines an atrial tachyarrhythmia based on the programmable Detect Rate and Detect Duration:

Detect Rate – The rates above which pacemaker-defined atrial tachyarrhythmia starts. Note that ventricular tracking is limited by the Upper Tracking Rate or the total atrial refractory period, even when the atrial rate rises above the Detect Rate.

Detect Duration – The minimum duration (in seconds) that the atrial tachyarrhythmia must persist above the Detect Rate before the rate is considered tachyarrhythmic.

When the A-A rate exceeds the Detect Rate and is sustained for the Detect Duration, the pacemaker assumes that atrial tachyarrhythmia is in progress.

The pacemaker first monitors for any four of the last seven consecutive A-A intervals that are shorter than the detect rate interval.

If these criteria are met, the pacemaker will extend PVARP and the VA interval to uncover any blanked AS events. If an A-A interval shorter than the detect rate interval is detected, 2:1 sensing of an atrial tachyarrhythmia is assumed. Otherwise, the pacemaker resumes monitoring for 2:1 sensing of atrial tachyarrhythmias in 90 seconds.

When an atrial tachyarrhythmia is detected, the pacemaker switches to the appropriate non-atrial tracking mode. To avoid an abrupt drop in the ventricular rate, it smoothly reduces the pacing rate from the atrial synchronous rate to the sensor-indicated rate over several pacing cycles.

After the rate transition is completed, the pacemaker continues sensor-driven pacing in the ventricle, operating in the non-atrial tracking mode until the atrial tachyarrhythmia ceases. When the last seven A-A intervals are longer than the upper tracking rate interval or when five consecutive atrial paces occur, the pacemaker assumes atrial tachyarrhythmia has ceased and begins to switch back to the programmed atrial tracking mode (DDDR, DDD, or VDD).

2.3 S Jude Medical - AMS

The St. Jude Medical (St. Paul, MN, USA) Auto Mode Switch (AMS) parameter prevents atrial-based timing modes from tracking atrial tachycardias and causing pacemaker-mediated tachycardia (PMT). The Auto Mode Switch algorithm switches the mode from DDD(R) to a ventricular-timing mode (DDI, DDIR, DDT, DDTR, VVT, VVTR, VVI, or VVIR)⁵ when the atrial rate surpasses the Atrial Tachycardia Detection Rate (ATDR) setting. At mode-switch, the device paces in the ventricle at the AMS Base Rate setting.

Rather than use the actual atrial rate, which cannot always distinguish between sustained tachycardia and intermittent fast cycles, AMS uses the Filtered Atrial Rate Interval (FARI), which is based on a comparison of the current atrial rate to a continually updated average rate. When the tachyarrhythmia subsides and the FARI falls below the AF Suppression™ Algorithm pacing-driven rate setting, Max Track Rate setting, or the Sensor-indicated rate (whichever is faster), the device switches back to the DDD(R) or VDD(R) mode.

Diagnostic data on mode switching can be found in the Mode Switch and AT/AF diagnostic.

The Atrial Tachycardia Detection Rate (ATDR) parameter sets the atrial rate at which the device mode-switches when the Auto Mode Switch parameter is enabled. A mode-switch occurs when the Filtered Atrial Rate Interval (FARI) exceeds the programmed ATDR setting. The device switches back to DDD(R) pacing when the FARI falls below the AF Suppression™ Algorithm pacing-driven rate, Max Track Rate setting, or the Sensor-indicated rate. The ATDR parameter is always available because it is also used to classify events in atrial tachycardia and trigger EGM storage.

2.4 Ela Medical Algorithm

AMS function in the Ela Medical pacemakers (ELA Medical, Montrouge, France) combines an initial UR switch at the onset of atrial tachyarrhythmias, followed by AMS based on the detection of a sustained atrial rate above a preset atrial tachyarrhythmias detection rate. The atrial tachyarrhythmia detection interval is termed the “diagnosis of atrial rhythm acceleration period.” This varies from 62.5% (for sinus rate 80 beats/min) to 75% of the preceding PP interval (for sinus rate 80 beats/min). At the onset of atrial tachyarrhythmia, only events outside the atrial tachyarrhythmia detection rate will be sensed and ventricular pacing triggered. This in effect switches the URI to the atrial tachyarrhythmia detection interval (termed “temporary mode switch” in the device). When 28 of 32 or 36 of 64 consecutive beats above the atrial tachyarrhythmia detection rate are detected, AMS will be initiated termed “permanent mode switch” in the device). A further refinement during AMS allows the pacer to function in the DDIR mode for spontaneous ventricular rate 100 beats/min, and VVIR mode when this rate. 100 beats/min to avoid atrial competitive pacing. Resynchronization to sinus rhythm occurs if 24 consecutive atrial cycles are, 110

beats/min. This counter will be reset if premature beats are sensed within this confirmation period until the 24 atrial/ventricular cycles, 110 beats/min are satisfied.

2.5 Vitatron algorithm

The Vitatron (Vitatron Medical BV, Dieren, the Netherlands) pacemakers have a different AMS algorithm that use a physiological band to define normal versus pathological atrial rate. A physiological atrial rate is calculated from the running average of the actual As or Ap atrial beats and the rate change in this moving average is limited to 2 beats/min. The physiological band is defined by an upper boundary equal to the physiological rate plus 15 beats/min (minimum value of 100 beats/min) and the lower boundary by the physiological rate minus 15 beats/min (or the sensor indicated rate if it is higher). As the physiological rate during sensor-driven pacing will be determined by the sensor, it follows that atrial tachyarrhythmia detection is sensor-based when the sensor is active. If an atrial event occurs above the upper boundary of the physiological band, AMS to DDIR mode will immediately occur. The ventricular escape rate is the sensor indicated rate or lower boundary of the the pacemaker detects a P wave in the TARP, an AV interval is not initiated and the atrial refractory period is extended by an amount equal to the TARP. If further atrial events are sensed within the new TARP (outside the atrial blanking period), the TARP is further extended, causing the pacemaker to function in the DVIR mode with ventricular-based LR timing. Instantaneous resynchronization occurs when an atrial event occurs outside the TARP, or when the LR has been reached and an Ap event is initiated. Although this algorithm functions effectively in a different mode (DVIR), it provides a sensitive and fast reacting response to onset and termination of atrial tachyarrhythmia. However, it has a low specificity and may result in frequent switching to DVIR pacing during noise and atrial ectopics. In addition, competitive (asynchronous) atrial pacing occurs during tachycardia, and may paradoxically reinduce AF should AF terminate spontaneously.

2.6 Biotronik algorithm

The Biotronik algorithm offers a choice of two algorithms that effectively repress the conduction of an atrial tachycardia in the ventricle. At the start of a tachycardic episode, the pacemaker automatically switches from an atrial-controlled to a ventricular-controlled mode.

The following functions are available:

- Automatic Mode Conversion
- X/Z-out-of-8 Mode Switching

3. Automatic mode conversion

This option is available in the atrial modes DDD(R) and VDD(R) as well as in DDT(R)/A and DDT(R)/V modes. In the case of tachycardias -- when the P-P interval is shorter than the ARP (atrial refractory period) -- this activates an automatic switch to a mode without atrial control. If the pacemaker is in DDD(R), DDT(R)/A, or DDT(R)/V mode, it switches to DVI(R); if it is operating in VDD(R) mode, it switches to VVI(R). This procedure prevents P-wave-triggered ventricular pacing during tachycardia.

When mode conversion is disabled, an atrial sensed event within the refractory period does not trigger an interval. In activated mode conversion, however, an atrial sensed event within the refractory period triggers a restart of the refractory period. The basic interval and the AV delay are not restarted. If the coupling interval between the consecutive P-waves becomes shorter than the atrial refractory period, the atrial refractory period will be continuously restarted. This means that the pacemaker remains refractory in the atrium during the entire basic interval.

This leads to non-P-wave-triggered AV sequential pacing with the basic rate for the duration of the atrial tachycardia.

3.1 Mode switching with X/Z-out-of-8 algorithm

This X/Z-out-of-8 algorithm can be used to program activation and deactivation criteria. This prevents unnecessary mode oscillations in the case of atrial extrasystoles or instable atrial signals. In addition, this algorithm can be employed to determine the speed at which a de- and resynchronization with ventricular depolarization ensues. This intervention rate can be programmed within a range from 100... (10)... (10)... 250 ppm.

In addition, the postventricular atrial blanking time (PVAB) after a ventricular event can be programmed in a range from 50 – 200 ms. This prevents any ventricular events in the atrial channel from being registered.

When an atrial tachycardia is detected, the pacemaker automatically switches to a non-atrial-controlled mode: from DDD(R) to DDI(R), from DDD(R)+ to DDI(R), or from VDD(R) to VDI(R) as well as from DDT(R)/A and DDT(R)/V to DDI(R).

The mode switch can be programmed so that you can switch from a non-rate-adaptive mode to a rate-adaptive mode, and vice versa. This serves to prevent an undesirable rate drop to the basic rate in case of physical stress.

An atrial tachycardia is considered sensed when the so-called Xout- of-8 conversion criterion has been fulfilled. The X value can be programmed in the value range ($X = 3... (1)...8$). Detection is based on the continual evaluation of the last 8 atrial intervals. When X out of 8 intervals reveal an atrial rate which lies above the programmed intervention rate, then the conversion criterion is fulfilled and mode switching automatically follows.

The pacemaker works in the programmed non-atrial mode until the switch-off criterion (Z-out-of-8) has been fulfilled. The Z value can be programmed in the value range ($Z = 3... (1)...8$). Likewise, the last 8 consecutive atrial intervals are continuously evaluated. When Z out of 8 intervals lie below the programmed intervention rate, the atrial tachycardia is considered to be over, and the pacemaker automatically switches to the originally programmed atrial-controlled mode.

The X or Z counter is reset to zero after every completed switching.

3.2 Sorin algorithm

The Sorin (Saluggia, Italy) pacemakers measure the “peak endocardial acceleration” with an implantable acceleration sensor at the tip of the right ventricular pacing lead. In addition, it also has a gravitational type of activity sensor. Atrial tachyarrhythmia is defined as atrial events at a rate exceeding the UR. In the DDD mode, on detection of atrial tachyarrhythmia, the pacemaker will mode switch to the VVI mode at the UR for 1,000 cycles before it falls back gradually to a nonprogrammable ventricular pacing rate of 77 beats/min. In the DDDR

mode using the activity sensor, the device will temporarily mode switch to the VVI mode at the UR for 250 cycles. Should the sinus rate fall below the UR during this period, AMS will not occur. This is designed to avoid AMS during nonexercise related sinus tachycardia. If the atrial rate remains above UR for 250 cycles, the sensor indicated interval is then checked. If there is a discrepancy between it and the As rate, the pacing rate will fall back to the sensor indicated rate. When the peak endocardial acceleration sensor DDDR mode is activated, the As rate above the UR will be compared with the sensor indicated rate. When the atrial rate is above the sensor indicated rate, the pacemaker will immediately mode switch to VVIR mode and the pacing rate will fall back to the sensor indicated rate. In activity and peak endocardial acceleration DDDR mode, atrial tracking resumes when three As cycles are at a rate lower than the UR.

3.3 AMS in VDD pacemakers

Stable long-term atrial sensing and ventricular stimulation have been demonstrated single-lead for VDD pacing with “floating” atrial electrodes. Many VDD pacemakers have AMS algorithms similar to their DDD counterparts. However, the absence of atrial pacing in VDD pacemakers prevents AV synchrony during atrial asystole after atrial tachy-arrhythmia termination or when the atrial rate drops below LR. Inadequate AV asynchrony may paradoxically predispose to AF. However, the absence of atrial pacing, particularly during atrial undersensing, may prevent inappropriate atrial pacing during AF as may occur with a DDDR pacemaker. Indeed, a recent short-term study in 23 patients with second- or third-degree AV block and paroxysmal AF showed that in the DDDR mode, inappropriate atrial pacing occurred in 50% patients despite mode switching. (27) In patients with AV block implanted with DDD pacemakers, 9.8% developed AF at a mean of 23 months. (28) In a report on patients with a singlelead VDD pacemaker, 9% developed AF over a follow-up of 5.5 years. (28-29). Thus, the incidence of AF between DDD and VDD appears comparable. Further studies will be required to compare the incidence of VDD versus DDD pacing in suppressing AF. (30)

4. Conclusions

Overall experience with AMS has been satisfactory so far. Barring economic considerations, all pacemakers should possess an AMS function as one of its programmable options. AMS allows the benefits of AV synchrony to be extended to a population with existing or threatened AF. These devices are indicated in all patients with the brady-tachy syndrome. They should also be considered in patients with sinus node disease without paroxysmal AF, obstructive hypertrophic cardiomyopathy, or any condition that predisposes patients to paroxysmal AF. Indeed, like the rate adaptive function (R), it could be argued that all patients should receive a device with AMS capability because one cannot predict which patients will eventually develop AF (or atrial chronotropic incompetence in the case of the rate-adaptive function). Many algorithms have been used by different manufacturers, and they do not behave similarly. Optimal care of the pacemaker patient requires a thorough knowledge of his or her arrhythmia history, atrial electrocardiogram amplitude (in sinus rhythm and atrial tachy-arrhythmia), basic timing cycles required for all AMS algorithms, and the characteristics of the various available algorithms.

<i>Devices</i>	<i>Pacing During AMS</i>
BOSTON SCIENTIFIC ALTRUA®	DDD (R) → DDI (R) , VDI (R)
GUIDANT INSIGNIA® / PULSAR® / MERIDIAN® / DISCOVERY®	DDD (R) → DDI (R) , VDI (R)
MEDTRONIC ENRHYTHM® / RELIA® / SENSIA® / VERSA® / ADAPTA®	DDD (R) → DDI (R) - VDD (R) → VDIR
VITATRON SERIE T / SERIE C	DDD (R) → DDI (R) , VDI (R)
S. JUDE MEDICAL IDENTITY® / VICTORY® / INTEGRITY® / ACCENT® / VERITY®	DDDR → DDIR - DDD → DDI
BIOTRONIK EVIA®	DDD (R) → DDI (R) , VDI (R)
BIOTRONIK CYLOS® / PHILOS®	DDD (R) → DDI (R) , VDI (R) , VVI (R) , DVI (R)
SORIN GROUP NEWLIVING® / ESPRIT® / NEWAY®	DDD (R) → DDI (R)
ELA MEDICAL REPLY® / RHAPSODY® / SYMPHONY® / TALENT®	DDD (R) → DDI (R)
MEDICO SOPHOS®	DDD (R) → DDI (R) , VDI (R)

Table I. Pacing Mode During Mode Switching

<i>Devices</i>	<i>Mode</i>
BOSTON / GUIDANT	PROGRAMMABLE NUMBER OF ATRIAL EVENTS < ATR
MEDTRONIC	(PROGRAMMABLE) NUMBER OF ATRIAL INTERVALS > PROGRAMMABLE SLOW INTERVAL
S. JUDE MEDICAL	FARI < MTR or MSR
BIOTRONIK	X/Z ON 8. PROGRAMMABLE NUMBER OF INTERVALS (X e Z) ON 8 WITH RATE < ATR
SORIN GROUP	ATRIAL RATE=FV
ELA MEDICAL	18/32 ATRIAL EVENTS OUT OF WARAD
MEDICO	PROGRAMMABLE NUMBER OF ATRIAL EVENTS < ATR

MTR= MAXIMUM TRACKING RATE; MSR= MAXIMUM SENSOR RATE ; ATR= ATRIAL TRACKING RATE, CUTOFF OF FAST ATRIAL RATE (PROGRAMMABLE); FARI= FILTERED ATRIAL RATE INTERVALS, based on current atrial rate confronted with average atrial rate ; WARAD= WINDOW OF ATRIAL RATE ACCELERATION DETECTION ; FV= MAXIMUM ATRIAL VARIATION RANGE STILL CONSIDERED SINUSAL VARIATION

Table II. Mode Switching Termination

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Address for corrispondance:

Maurizio Santomauro, MD, FESC, FHRS

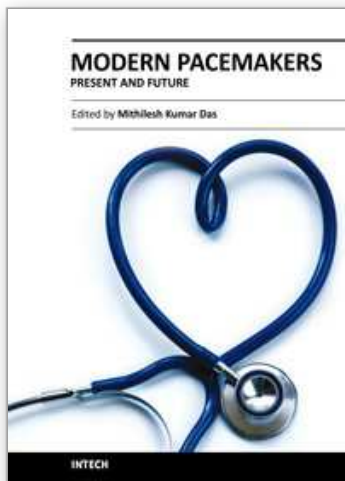
Department of Medicine, Cardiology and Immunology

Federico II School of Medicine, University of Naples

Via Sergio Pansini 5

80131 Naples, Italy

santomau@unina.it



Modern Pacemakers - Present and Future

Edited by Prof. Mithilesh R Das

ISBN 978-953-307-214-2

Hard cover, 610 pages

Publisher InTech

Published online 14, February, 2011

Published in print edition February, 2011

The book focuses upon clinical as well as engineering aspects of modern cardiac pacemakers. Modern pacemaker functions, implant techniques, various complications related to implant and complications during follow-up are covered. The issue of interaction between magnetic resonance imaging and pacemakers are well discussed. Chapters are also included discussing the role of pacemakers in congenital and acquired conduction disease. Apart from pacing for bradycardia, the role of pacemakers in cardiac resynchronization therapy has been an important aspect of management of advanced heart failure. The book provides an excellent overview of implantation techniques as well as benefits and limitations of cardiac resynchronization therapy. Pacemaker follow-up with remote monitoring is getting more and more acceptance in clinical practice; therefore, chapters related to various aspects of remote monitoring are also incorporated in the book. The current aspect of cardiac pacemaker physiology and role of cardiac ion channels, as well as the present and future of biopacemakers are included to glimpse into the future management of conduction system diseases. We have also included chapters regarding gut pacemakers as well as pacemaker mechanisms of neural networks. Therefore, the book covers the entire spectrum of modern pacemaker therapy including implant techniques, device related complications, interactions, limitations, and benefits (including the role of pacing role in heart failure), as well as future prospects of cardiac pacing.

How to reference

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Maurizio Santomauro, Carlo Duilio, Carla Riganti, Paolo Di Mauro, Gennaro Iapicca, Luca Auricchio, Alessio Borrelli and Pasquale Perrone Filardi (2011). Different Automatic Mode Switching in DDDR Pacemakers, *Modern Pacemakers - Present and Future*, Prof. Mithilesh R Das (Ed.), ISBN: 978-953-307-214-2, InTech, Available from: <http://www.intechopen.com/books/modern-pacemakers-present-and-future/different-automatic-mode-switching-in-dddr-pacemakers>

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InTech Europe

University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447

InTech China

Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820

Fax: +385 (51) 686 166
www.intechopen.com

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