A Review on Pacemakers: Device Types, Operating Modes and Pacing Pulses. Problems Related to the Pacing Pulses Detection.

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Abstract: *A pacemaker is a small battery-operated medical device that delivers electrical impulses to the heart in order to guarantee regular contractions. Depending on the number of active leads the pacemakers are single chamber, dual chamber and bi-ventricular. According to their programming the devices could be with fixed-rate, 'on demand' and rate-responsitive. The operating mode of the pacemaker depends on the paced chamber, the sensed chamber, the response to a sensed electrical signal and the rate modulation. Two types of pacing are recognized – unipolar and bipolar, represented with different pacing artifacts in the ECG signal.*

The pacing pulse on the skin surface usually have very fast rising edges of the order of 10 µs or less and could be as small as few hundreds µV. The pacing artifacts detection is important since they indicate the presence of a pacemaker and help to evaluate the reaction of the heart. All pertinent medical standards require the pacing artifacts to be captured and indicated on the screen of the device.

This paper presents a short review on pacemakers – reasons for implementation, device types, different operation modes and pacing pulses. It reveals some common problems with the detection of pacemaker's artifacts.

Keywords: *Electrocardiogram, Pacemaker, Types, Modes, Artifacts.*

Introduction

The heart is a muscular organ that provides a continuous blood circulation through the human's body. In normal situation the heart beats are regular and they appear from 60 to 100 beats per minute (bpm). The heart rate could be much faster due to physiological reasons – physical activity of the person, pain, stress, etc.

The heart is composed by two upper chambers – left and right atria, and two lower chambers – left and right ventricles. The blood circulation within one heart cycle is performed in two loops.

Pulmonary loop:

- The oxygen-poor blood enters the right atrium via superior and inferior vena cava.
- The right atrium pumps the blood into the right ventricle through a tricuspidal valve.
- The right ventricle contracts and pumps the blood through the right and left pulmonary arteries to the lungs for oxygenation.

Systemic loop:

- The oxygen-rich blood from the lungs passes through the pulmonary veins and enters the left atrium.
- The left atrium pumps the blood into the left ventricle through a mitral valve.
- The left ventricle contracts and pumps the oxygen-rich blood through the aorta to the body.

The regular contractions of the heart are managed by heart's electrical system that includes three important parts:

- Sinoatrial (SA) node – known as the heart's natural pacemaker. In healthy heart it leads the heart rhythm.
- Atrioventricular (AV) node – bridge between the atria and ventricles. It passes the electrical signals from the atria to the ventricles.
- His-Purkinje system – it carries the electrical signals throughout the ventricles and includes His bundle, Right bundle branch, Left bundle branch and Purkinje fibers.

The electrocardiogram (ECG) is a recording of the electrical activity of the heart (Fig. 1). The stimulus from the SA node causes atria contraction registered as P-wave on the ECG. The signal arrives at the AV node where it is slowed to allow the blood-filling of the ventricles. This interval is represented by a flat line in the ECG between P- and Q-waves. Then the signal spreads through the ventricles (Q-wave), causing their contraction, which is represented by the most significant wave in the ECG – the QRS complex. The R-wave corresponds to the contraction of left ventricle and S wave represents the contraction of right ventricle. The following T-wave in the ECG signal represents the ventricles' relaxation.

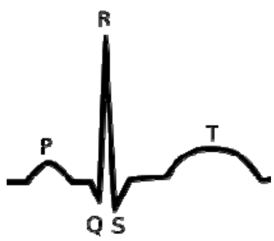

Fig. 1 ECG segment representing one heart cycle

A problem in the heart's electrical system can disrupt the heart's normal rhythm. A pacemaker is a small battery-operated medical device that delivers electrical impulses to the cardiac muscles in order to guarantee regular heart contractions and normal blood circulation, thus preventing from cardiac arrest and eventual death. Modern pacemakers stimulate the myocardium, sense intrinsic cardiac activity and can store a variety of data from the heart signals and the pacing system [3]. They include pulse generator and one or more pacing leads which transmit the electrical impulses from the pulse generator to the heart and from the heart back to the pulse generator. Depending on the underlying heart disease, the pacemaker could be programmed to pace upper chambers, lower chambers or both. The American College of Cardiology and the American Heart Association published clinical guidelines for permanent pacemaker implantation, where the selection of pacemaker type according to the patient's indications is analyzed in details [4].

The aim of this review is to give a brief outline of the indications for pacing, the different types of pacemakers and their operation modes, as well as to figure some common problems for the detection of the pacing artifacts.

Indications for pacemaker

The normal resting heart rate ranges from 60 to 100 bpm. Normally, the SA node automatically maintains a heart rate to be adequate for the oxygen needs of the body – e.g. decreases during sleep and increases during exercise. Problem with the heart's electrical system could lead to decrease/increase of the heart rate, lack of synchronization between atria and ventricular contractions manifested by prolonged PR intervals, dropped QRS complexes, wide QRSes, etc. which could lead to decrease in the functional status and the life quality of the patient or even to death. The most common reasons for pacemaker implantation are [5]:

- SA node dysfunction leading to sinus bradycardia, including frequent sinus pauses;
- AV or intraventricular conduction block, when the signals from SA node are normal but fail to be transmitted between the atria and the ventricles or within the ventricles;
- Tachyarrhythmias including atrial flutter, paroxysmal reentrant ventricular tachycardia (VT) and VT.

Pacemaker types

There are different pacemaker types depending on the number of active leads placed in the heart and the pacemaker programming.

Pacemaker types according to the number of leads

- *Single chamber pacemaker*

This pacemaker uses one electrode in the right atrium or right ventricle of the heart. The electrode is placed in right atrium when the sinus node is generating pulses that are too slow or irregular (sinus bradycardia, atrial flutter). However, to use this method of pacing, the rest of the heart's conduction system must be functioning normally.

More commonly, the single electrode is placed in right ventricle to help correct a slow or irregular heartbeat. This is most often the case when the electrical flow is slowed or blocked in the region of the AV node and the normal impulses from the atria cannot reach the ventricle, thus producing too slow heartbeat.

- *Dual chamber pacemaker*

This pacemaker uses one electrode into the upper chamber and one electrode in the lower chamber of the heart. This type of pacing most closely mimics the heart's normal conduction pattern by pacing sequentially from atria to ventricle thus maximizing the heart's pumping ability. By having electrodes in both the atria and ventricle, the pulse generator is able to continuously regulate the heart's electrical activity in both chambers. These are the most commonly used pacemakers nowadays.

- *Bi-ventricular pacemaker*

This pacemaker uses three leads – first into right atrium, second into right ventricle and third into the left ventricle. It is applied when both ventricles do not contract at the same time and are not synchronized with the atria. In case of heart failure, often the right and left ventricles do not pump together. When the heart's contractions become unsynchronized, the left ventricle is not able to pump enough blood to the body. In such cases bi-ventricular pacing, also called cardiac resynchronization therapy (CRT) is applied.

Pacemaker types according to the programming

- *A fixed-rate pacemaker*

Such a device produces pace pulses at a steady rate, regardless of the heart's own electrical activity. A fixed-rate pacemaker cannot detect intrinsic heartbeats and emits electrical impulses at the same time when the heart's own pacemaker fires, causing competitive beats.

- *Pacemaker "on demand"*

Such a device monitors the heart rhythm and generates electrical pulses only if the heart is beating too slowly or if it misses a beat. The advantage of a pacemaker on demand over the fixed-rate pacemakers is that they prevent from the occurrence of competitive beats and keep their battery for a longer period.

- *Rate-responsive pacemaker*

Such a device speeds up or slows down the heart rate depending on how active is the person. The optimal heart rate is determined by additional sensor for person's activity based on body movement or a breathing sensor, which detects the respiration rate.

Pacemaker operating modes

The operating mode of the pacemaker is coded with 4 letters [6]. The 1st letter indicates the chamber that is paced – A for atrium, V for ventricle, D (dual) for both. The 2nd letter indicates the chamber that is sensed, enrolling the above abbreviations with an additional one – O for none. The 3rd letter refers to the response to a sensed electrical signal and indicates whether a pace is inhibited or triggered. Inhibition of pace is done when there is an intrinsic beat sensed in the chamber and a new timing cycle starts. In triggered mode, stimulus is emitted in one chamber in response to a sensed event in the other chamber. The used codes are I for inhibition of pace in the sensed chambers, T for triggering in the sensed chambers, D for dual (inhibition + trigger) and O stands for none. The 4th letter represents the rate modulation. It can be R for rate modulation and O for no rate modulation. These rate-responsive modes are implemented in rate-responsive pacemakers and they will not be discussed in this paper.

VOO mode: Pace ventricle, sense nothing, no response

Ventricular asynchronous pacing is the simplest pacing mode with neither sensing nor mode of response. The ventricular pacing occurs at the programmed lower rate interval (LRI) regardless the intrinsic activity in the heart (Fig. 2).

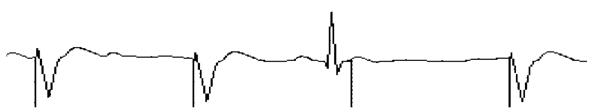

Fig. 2 VOO mode: the intrinsic ventricular beat is not sensed and the following pacing pulse is not inhibited

AOO mode: Pace atrium, sense nothing, no response

This mode is similar to VOO with the only difference that instead of ventricle the atrium is paced after every LRI (Fig. 3).

Fig. 3 AOO mode: pacing precedes each P-wave

DOO mode: Pace atrium + ventricle, sense nothing, no response

The DOO timing cycle consists of defined AV and ventricular-atrial (VA) intervals. VA interval is a function of the AV and ventricular-ventricular (VV) intervals. The intervals do not vary because no activity is sensed. An example of this mode is presented in Fig. 4.

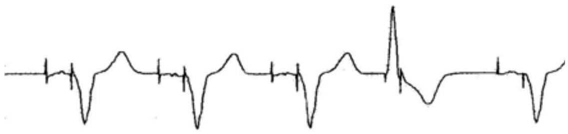

Fig. 4 DOO mode: the 4th intrinsic ventricular beat is not sensed
and the following pacing pulse is not inhibited

Pacemakers running AOO, VOO, DOO modes were popular in the early days of pacemaker technology because they worked well and were electronically simple. Nowadays, pacemakers without sensing abilities are rarely used.

VVI mode: Pace ventricle, sense ventricle, inhibit pacing

In this mode, the pacemaker paces the ventricle and senses the electrical activity in the ventricle. Initially LRI is set for a programmed interval, which starts with a sensed or paced ventricular event. During this LRI, the pacemaker senses and when there is an intrinsic ventricular beat it inhibits the pacing pulse and LRI is reset. In the opposite case, if ventricular beat is not sensed until the end of LRI, the pacemaker paces the ventricle and again LRI is reset. VVI pacemakers are refractory after a paced or sensed ventricular event – a period known as ventricular refractory period (VRP). Any ventricular event occurring within the VRP is not sensed and does not reset the LRI. An example of this mode is presented in Fig. 5.

VVI is the most commonly used pacing mode. It protects from lethal bradycardias but it does not restore or maintain atrioventricular synchrony and does not provide rate responsiveness.

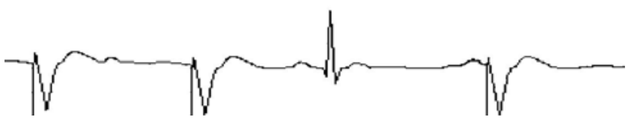

Fig. 5 VVI mode: the 3rd intrinsic ventricular beat is sensed
and the following pacing pulse is inhibited

AAI mode: Pace atrium, sense atrium, inhibit pacing

AAI pacing, incorporates the same timing cycles as VVI, with the obvious differences that pacing and sensing occur from the atrium and pacemaker output is inhibited by a sensed atrial event. In this mode, LRI starts from an atrial event. An atrial paced or sensed event initiates an atrial refractory period (ARP) during which the pacemaker senses nothing. Any intrinsic atrial beat within this ARP is not sensed and LRI is not reset. An example of AAI mode is presented in Fig. 6.

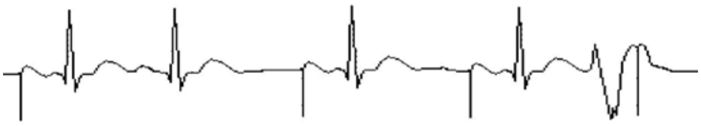

Fig. 6 AAI mode: the intrinsic atrial activity during the 2nd beat is sensed and the following pacing pulse is inhibited. However, the 5th beat (ventricular extrasystole) is not sensed and a pacing pulse is visible immediately after it during the T-wave. Such pacing is very dangerous and could initiate ventricular fibrillation.

DDD mode: Pace atrium + ventricle, sense atrium + ventricle, inhibit + trigger pacing

In this mode (Fig. 7) the pacemaker paces both the atrium and ventricle and also senses the electrical activity both in atrium and ventricle. If some intrinsic activity is found in atrium, it inhibits the pace but triggers a pace in the ventricle after the AV interval. If there is an intrinsic activity in the ventricle, the pace in the ventricle is also inhibited.

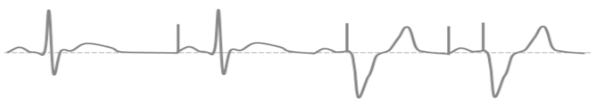

Fig. 7 DDD mode: 2nd beat – paced atrium, 3rd beat – paced ventricle, 4th beat – paced both atrium and ventricle

DVI mode: Pace atrium + ventricle, sense ventricle, inhibit pacing

In atrio-ventricular sequential (called sequential demand) mode (Fig. 8), both right atrium and right ventricle are paced but only the ventricle is sensed. The DVI timing cycle consists of defined AV and VV intervals. The VA interval is a function of the AV and VV (LRI) intervals. Both chambers are paced at the same rate separated by a fixed AV sequential interval. The ventricles are paced if the defined AV interval expires and there is no sensed intrinsic ventricular beat. If there is some intrinsic ventricle beat within the AV interval, the pace of the ventricle is inhibited but the VA interval is not reset. As there is no sensing in atria, even though there is some intrinsic atrial beat in the VA, the pace is not inhibited and the pacemaker paces atria when the VA interval expires.

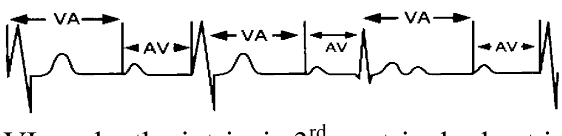

Fig. 8 DVI mode: the intrinsic 3rd ventricular beat is sensed and the ventricle is not paced. The intrinsic P-wave after it is not sensed and the atrium is paced when VA interval expires.

DDI mode: Pace atrium + ventricle, sense atrium + ventricle, inhibit pacing

In this mode, sensed atrial activity inhibits the atrial pacing but does not trigger a ventricular pace pulse, i.e. atrial sensed event does not produce a physiological AV delay and if intrinsic ventricular beat is not sensed the ventricles are paced when VV interval elapsed. This mode is developed to deal mainly with atrial tachyarrhythmias, such as atrial fibrillation when the ventricles should not be forced to follow the high atria rate. An example of DDI mode is presented in Fig. 9.

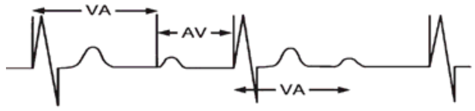

Fig. 9 DDI mode: the intrinsic atrial activity before the 3rd QRS inhibits atrial pacing and the ventricles are paced after (VA + AV) period elapsed

VDD mode: Pace ventricle, sense atrium + ventricle, inhibit + trigger pacing

In this mode (Fig. 10), pacemaker paces only the ventricle, senses both atrium and ventricle, and responds by both inhibition of ventricular pace when intrinsic ventricular activity is sensed and triggering a ventricular pace in response to an intrinsic P-wave.

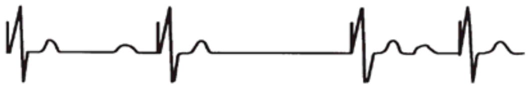

Fig. 10 VDD mode: the interval between 2nd and 3rd beat is the LRI and the pacing is triggered by the activity in the ventricle. All other paces are triggered by the atrium activity.

VAT mode: Pace ventricle, sense atrium, trigger pace in ventricle

In this mode (Fig. 11), ventricle is paced after every LRI even if there is ventricular beat in the LRI (no ventricular sensing, no inhibition). The atrium is sensed and if intrinsic atrial activity is found, ventricular pace after AV interval is triggered in the ventricle and a new LRI is started. VAT mode can be used in patients with complete heart block with normal sinus and atrial electrical function, but it should be avoided when an abnormality of sinus or atrial function is present.

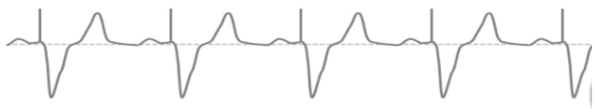

Fig. 11 VAT mode: ventricle is paced after each P-wave

VVT mode: Pace ventricle, sense ventricle, trigger pace in ventricle

In this mode (Fig. 12), ventricle is paced and sensed. If there is any intrinsic activity sensed in the ventricle, a ventricular stimuli is triggered. When there is no spontaneous electric activity sensed in the ventricle outside the VRP, the ventricle is paced at the LRI cycle. In VVT the pacemaker delivers a pulse not only when no ventricular event has been sensed within a preset LRI but also generates pace pulses triggered by any spontaneous ventricular event within the preset LRI. This mode is invented to overcome difficulties that the earlier VVI pacemaker encountered when exposed to magnetic interference and the pacemakers falsely inhibited the delivery of pacing pulses. VVT is rarely used only when a patient is routinely exposed to electromagnetic interference. Its general drawback is that it may cause tachyarrhythmias.

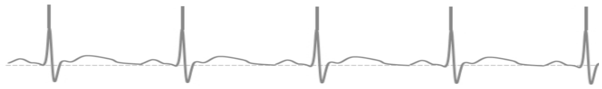

Fig. 12 VVT mode: the pace pulses are over the QRS complexes

AAT mode: Pace atrium, sense atrium, trigger pace in atrium

In this mode (Fig. 13), atrium is paced and sensed. If there is any intrinsic activity sensed in the atrium, an atrium stimuli is triggered. When there is no spontaneous electric activity sensed in the atrium outside the ARP, the atrium is paced at the LRI cycle. In theory, this mode is used when due to symptomatic skeletal muscle sensing, the AAI mode cannot be used.

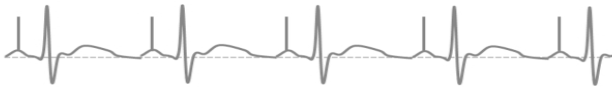

Fig. 13 AAT mode: the pace pulses are over the P-waves

Bi-ventricular pacing

In this mode, to provide AV-synchronous ventricular pacing it is crucial the proper atrial sensing. In case of correct atria function only the ventricles are paced (Figure 14a), otherwise the atrium is also paced (Fig. 14b).

(a) (b)

Fig. 14 Bi-ventricular pacing: (a) paced ventricles, (b) paced atrium and ventricles

Pacemaker pulses

The pacemaker supplies electrical current between two electrodes. These two electrodes may be either on the pacemaker lead, or one electrode on the pacemaker lead and the other is the metal covering of the pacemaker pulse generator. When the current flows between the two electrodes on the pacemaker lead, this is referred to as bipolar pacing. If the current flows between the tip of the lead and the pacemaker generator, this is referred to as unipolar pacing. Bipolar and unipolar pacing have different appearances on surface ECGs. In unipolar pacing, the current flows through a large area of the body between the tip of the lead and the pulse generator. Unipolar pacing, therefore, creates a large stimulus artifact (several hundred mV magnitude and width of a couple of ms) on the surface ECG. The bipolar pacing, the distance between the two poles that deliver current is very small (about a centimeter) and the stimulus are much smaller and may be very difficult to be seen on the surface ECG. The pacing pulse on the skin surface could be as small as few hundred μV, width 25 μs, with average artifacts 1 mV high and 500 μs wide. Most pacing pulses have very fast rising edges with duration 10 μs or less [7].

It is important to be able to detect pacing artifacts since they indicate the presence of a pacemaker and help to evaluate the reaction of the heart. All pertinent medical standards demand the display of pacing artifacts with varying requirements regarding the height and width of the pace pulse that has to be captured and indicated on the screen of the device.

The ANSI/AAMI IEC60601-2-27 [1] states that the equipment should be capable to display the ECG signal in the presence of pacemaker pulses with amplitudes of ±2 mV to ±700 mV and duration of 0.5 ms to 2.0 ms, while in ANSI/AAMI EC11 [2] the requirements are for amplitudes between 2 mV and 250 mV, durations in the range 0.1 ms to 2 ms and rising time less than 100 µs.

Problems with pace pulses detection

The typical pacing pulse is bipolar, which is required in order to leave the heart tissue with zero charge after the pacing (Fig. 15). Its positive phase has fast rising edge (duration about 10 µs at the body surface), a capacitive drop after its maximal amplitude, followed by a trailing edge. The negative phase appears during the recharge portion of the pacing pulse.

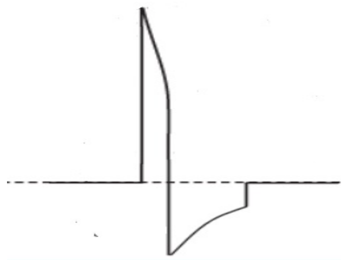

Fig. 15 A typical pacing pulse

The real pacing artifacts recognition is a challenge and some of the pacing pulse morphologies demand a significant increase in the complexity of the algorithms for detection [8].

The accuracy of pacing pulses detection is assessed by two statistical indices:

- Sensitivity $Se = TP/(TP + FN)$, where TP stands for the true positive detections and FN for the false negative (missed) detections;
- Positive predictive value $PPV = TP/(TP + FP)$, where FP stands for false positive detections.

In this respect, there are two types of errors that are discussed in details in [8]:

- *Missed pace pulses due to small amplitude or abnormal shape*

- Although the AAMI standards [1, 2] state that a patient monitor must detect pace pulses with amplitudes between 2 mV and 700 mV, modern pacemakers could generate smaller pacing pulse amplitude, which could fall below the detection threshold. One way to cope with this problem is decreasing the detection threshold which will inevitably lead to extra detections and additional logic for rejection of the falsely detected pacing pulses. Another solution is to analyze multiple ECG leads and to apply cross-check over the detections.

- The detection of abnormally shaped pacing pulses could be improved by searching for the abnormal pace pulse pattern in the analyzed ECG lead and verifying the existence of another repetitive pattern at the same time-moments in the other ECG leads.

- CRT devices add another degree of complication in detecting and displaying pacing artifacts [7]. They pace the patient in the right atrium and both ventricles. The pulses in the two ventricles can fall close together, overlap, or occur at exactly the same time; and the left ventricle can even be paced before the right ventricle. Detecting both ventricular pacing pulses separately is not always possible. When the two pulses are within a small time interval, the resulting pulse shape could be very complex. To address this complication, the authors in

[8] look not only at the coupling intervals within a series of two or three potential pace pulses but they take a more global look at the history of many timing intervals in combination with the corresponding potential pace pulse morphology to differentiate a pace pulse from a noise pulse and identify CRT pacing.

- *False pace pulse detection*

Motion artifacts, muscle noises, minute ventilation pulses, telemetry signals and noises conducted from other medical devices connected to the patient could lead to false pace pulse detection. The motion artifacts and EMG noises are well-known sources of errors in ECG analysis. The minute-ventilation pulses (used for control of the pacing rate in rate-responsive pacemakers) are always less than 100 μs wide, varying from about 15 μs to 100 μs and therefore could lead to false pace pulse detection. Another major noise source is the H-field telemetry scheme used by most implantable heart devices. To avoid such errors one can set requirements for repeatable morphology, reasonable time-interval between pulses, appearance in more than one ECG lead. When there is noise and pace pulses occurring simultaneously, preventing false pace detections while detecting true pace pulses becomes more complicated [8].

The problem with the detection of very low-amplitude or smoothed pacing artifacts on the surface ECG (Fig. 16a), bi-ventricular pacing with short coupling interval (Fig. 16b) should be considered together with the troubles that the false detection of steep and high amplitude artifacts (Fig. 16c) could cause.

(a)

(b)

(c)

Fig. 16 Examples presenting some problems faced
by the algorithm for pacing pulses detection:
(a) Low amplitude pacing pulses, visible in lead I but not visible in lead II.
This pulses could not be detected by analyzing only lead II.
Even in lead I the pace pulse is with very low amplitude.
(b) Bi-ventricular pacing with short coupling intervals
that overlap for some of the QRSes.
(c) Peak artifact that is high and steep enough to be
wrongly detected as pacing pulse (on demand).

Aiming at correct pacing artifacts detection, the algorithm should be applied on high-resolution ECG [9, 10] that preserves the steep slope of the pacing pulse.

Conclusion

This paper is a review on the great variety of available pacemaker types, according to the number of leads (single chamber, dual chamber, bi-ventricular) and their programming (fixed-rate, on demand, rate-responsive). It describes their operation modes, which depend on the paced chamber, the sensed chamber, the response to a sensed electrical signal and the rate modulation. The different modes abbreviations that cause difficulties even to experienced people in the field are addressed and examples of ECG signals that could help the understanding of the respective mode are presented. The two types of pacing pulses (unipolar and bipolar) are discussed. The paper figures some challenges for the pace pulses detection algorithms, such as low amplitude, abnormal shape, and complications caused by CRT devices that could lead to missed pace pulse, together with some noises (motion artifacts, muscle noises, minute ventilation pulses, telemetry signals, etc.), which could cause false pace pulse detection. Potentials for improvements, discussed in the literature, are mentioned. The information summarized in this review makes it useful as a background for development of an accurate algorithm for pacing pulses detection.

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